

EFFECT OF SHAPE AND SIZE OF END SILL ON HYDRAULIC ENERGY DISSIPATION BEHAVIOUR IN INCLINED SPILLWAY

THESIS

Submitted to the

G. B. Pant University of Agriculture and Technology
PANTNAGAR-263145, (U. S. NAGAR), Uttarakhand, INDIA



By

Shatruhan Jaiswal

**IN PARTIAL FULFILMENT OF THE
REQUIREMENTS FOR THE DEGREE OF**

Master of Technology

In

Agricultural Engineering

(Soil and Water Conservation Engineering)

June, 2015

VISIT...

LANZAROTE
Caliente.COM

ACKNOWLEDGEMENT

Achieving a milestone for any person alone is extremely difficult. However, there are motivations that come cross the curvaceous path like twinkling stars in the sky and make my task easier.

I take this golden opportunity to express my heartfelt and deepest sense of gratitude to those who have helped me to complete this manuscript. My debt many individuals can warmly be acknowledged but never full recompensed.

First, I would like to express my gratitude and respect to my advisor and chairperson of advisory committee, Dr. Akhilesh Kumar Professor, Department of Soil and Water Conservation Engineering for all I have learned from him and his invaluable motivation, sincere guidance, encouragement and support in all stages of this thesis. I would also like to thank him for being an open person to ideas and helping me to shape my interest and ideas.

The author expresses his deep sense of gratitude to members of his advisory committee Dr. Devendra Kumar, Professor & Head, Dr. Akhilesh Kumar, Professor, and Dr. P S Kshyap, Associate professor Department of Soil and Water Conservation Engineering for giving me the valuable suggestions and help during the thesis work. Special thanks are also due to Dr P V Singh, JRO in the Department for being a Member of the Advisory Committee for most part of the degree program. Recently he left the department to join at Ranichauri.

I am also greatly indebted to Dr. H. C. Sharma, Dean College of Technology and Dr. N. S. Murthy Dean, College of Post Graduate Studies, G. B. Pant University of Agriculture and Technology, Pantnagar for providing necessary facilities as and when needed to conduct this investigation.

Thanks to Ms. Meena Singh, typist in department of soil and water conservation engineering and Mr. M. R. Yadav, Mr. Badre Alam lab technician for extending their helping hands during the research work.

I express my thanks to the Almighty God for giving me courage and inspiration without which I would not have succeeded in my pursuit.

I am really short of words to express my sense of reverence and indebtedness to my beloved Mammi, Papa, and my brother Subhas Chandra Jaiswal and for all the academic and non-academic support which I have been enjoying from them. Without their unhesitating go ahead benediction, my dream of higher studies would have remained a chimera.

It is often said good friends are rare to get. In this context I find myself very lucky to have friends like Bhagwat Saran, Vijay Kumar, Sushil Kumar Maurya, Vivekanand, Prateek Singh, Anita, Pragati Sawnt, Shreya Nivesh, and Juhi Jaiswal & loving seniors, Sachin Kumar Singh, Saurabh singh, Rajdax panwar, Anurag Malik, Ajeet Kumar Yadav, Ashima and beloved juniors Ritun, Ashish, and Sonam Sandeep & for getting all sorts of help from them during my stay in this university.

Still there are many more loved ones, well-wishers; friends, relatives such as who directly or indirectly rendered us valuable help and moral strength to complete this academic endeavour. I have deep sense of reverence for all of them being always with me in up & downs of my life.

The author was recipient of TEQIP Assistantship during his M.Tech. Degree program.

In the last but not least we praise and thanks to God Almighty whose benevolent blessings always keep me on the right track,

Pantnagar
June, 2015


(Shatruhan Jaiswal)
Author

CERTIFICATE

This is to certify that the thesis entitled “**EFFECT OF SHAPE AND SIZE OF END SILL ON HYDRAULIC ENERGY DISSIPATION BEHAVIOUR IN INCLINED SPILLWAY**” submitted in partial fulfilment of the requirements for the degree of **MASTER OF TECHNOLOGY IN AGRICULTURAL ENGINEERING** with major in *Soil and Water Conservation Engineering*, of the College of Post Graduate Studies, G. B. Pant University of Agriculture & Technology, Pantnagar, is a record of *bona fide* research carried out by **Mr. Shatruhan Jaiswal, Id. No. 45822**, under my supervision, and no part of the thesis has been submitted for any other degree or diploma.

The assistance and help received during the course of this investigation and source of literature have been duly acknowledged.

**Pantnagar
June, 2015,**


(Akhilesh Kumar)
Chairman
Advisory Committee

CERTIFICATE

We, the undersigned, members of the Advisory Committee of **Mr. Shatruhan Jaiswal, Id. No. 45822**, a candidate for the degree of **MASTER OF TECHNOLOGY IN AGRICULTURAL ENGINEERING** with major in **SOIL AND WATER CONSERVATION ENGINEERING**, agree that the thesis entitled **“EFFECT OF SHAPE AND SIZE OF END SILL ON HYDRAULIC ENERGY DISSIPATION BEHAVIOUR IN INCLINED SPILLWAY”** may be submitted in partial fulfilment of the requirements for the degree.



(Akhilesh Kumar)
Chairman
Advisory Committee



(Devendra Kumar)
Member



(P. S. Kashyap)
Member

CONTENTS

C. NO.	TITLE	PAGE NO
1	INTRODUCTION	
2	REVIEW OF LITERATURE	
3	MATERIALS AND METHODS	
	3.1 Description of Materials Used	
	3.1.1 An inclined spillway	
	3.1.2 SAF Stilling basin	
	3.1.3 Chute blocks and Floor blocks	
	3.1.4 End sill	
	3.1.5 Water storage tank	
	3.1.6 Water delivery and circulation system	
	3.1.7 Discharge regulation system	
	3.1.8 Centrifugal pump	
	3.1.9 Hook gauge/point gauge	
	3.1.10 Measuring cylinder	
	3.1.11 Stop watch	
	3.2 Methodology Adopted	
	3.2.1 Fabrication of end sills of different shapes and heights	
	3.2.2 Development of Experimental Set-Up	
	3.2.2.1 Assembling of water supply line	
	3.2.2.2 Installation of inlet to source tank	
	3.2.2.3 Fixing SAF stilling basin with delivery tank	
	3.2.2.4 Fixing different shapes and size of end sill	
	3.2.2.5 Filling storage tank	
	3.2.2.6 Regulation of discharge	
	3.2.3 Experimentation and observations	
	3.2.3.1 Recording of hydraulic jump parameters	
	3.2.3.3 Determination of hydraulic jump efficiency and relative loss of energy	
	3.3 Analysis of Observed Data	

4.0 RESULTS AND DISCUSSION

4.1 Hydraulic Energy Dissipation Behaviours Using Different Shapes for a particular Heights of End Sill at Selected Discharges

- 4.1.2 Hydraulic energy dissipation behaviours using different shapes for a 3 cm height of end sill at selected discharges
- 4.1.3 Hydraulic energy dissipation behaviours using different shapes for a 4 cm height of end sill at selected discharges
- 4.1.4 Hydraulic energy dissipation behaviours using different shapes for a 5 cm height of end sill at selected discharges

4.2 Hydraulic Energy Dissipation Behaviours Using Different Heights of End Sill for a particular Shape at Selected Discharges

- 4.2.1 Hydraulic energy dissipation behaviour using different heights for rectangular shape of end sill at selected discharges
- 4.2.2 Hydraulic energy dissipation behaviour using different heights for triangular shape of end sill at selected discharges
- 4.2.3 Hydraulic energy dissipation behaviour using different heights for semi-circular shape of end sill at selected discharges
- 4.2.4 Hydraulic energy dissipation behaviour using different heights for diagonal vertical upstream shape of end sill at selected discharges
- 4.2.5 Hydraulic energy dissipation behaviour using different heights for diagonal vertical downstream shape of end sill at selected discharges

4.3 Relative Loss of Energy and Hydraulic Jump Efficiency Using Different Shapes for particular Height of End Sill at Selected Discharges

- 4.3.1 Relative loss of energy and hydraulic jump efficiency using different shapes for 3 cm height of end sill at selected discharges
- 4.3.2 Relative loss of energy and hydraulic jump efficiency using different shapes for 4 cm height of end sill at selected discharges

4.3.3 Relative loss of energy and hydraulic jump efficiency using different shapes for 5 cm height of end sill at selected discharges

4.4 Relative Loss of Energy and Hydraulic Jump Efficiency Using Different Heights for particular Shape of End Sill at Selected Discharges

4.4.1 Relative loss of energy and hydraulic jump efficiency using different heights for rectangular shape of end sill at selected discharges

4.4.2 Relative loss of energy and hydraulic jump efficiency using different heights for triangular shape of end sill at selected discharges

4.4.3 Relative loss of energy and hydraulic jump efficiency using different heights for semi-circular shape of end sill at selected discharges

4.4.4 Relative loss of energy and hydraulic jump efficiency using different heights for diagonal vertical upstream shape of end sill at selected discharges

4.4.5 Relative loss of energy and hydraulic jump efficiency using different heights for diagonal vertical downstream shape of end sill at selected discharges

4.5 Height of Jump Using Different Shapes for particular Height of End Sill at Selected Discharges

4.5.1 Height of jump using different shapes for 3 cm height of end sill at selected discharges

4.5.2 Height of jump using different shapes for 4 cm height of end sill at selected discharges

4.5.3 Height of jump using different shapes for 5 cm height of end sill at selected discharges

5 SUMMARY AND CONCLUSION

LITERATURE CITED

APPENDICES

VITA

LIST OF TABLES

TABLE NO	TITLE	PAGE NO
4.1	Observed hydraulic jump parameters and energy dissipation for different discharges using selected shapes and end sill height 3 cm	
4.2	Observed hydraulic jump parameters and energy dissipation for different discharges using selected shapes and end sill height 4 cm	
4.3	Observed hydraulic jump parameters and energy dissipation for different discharges using selected shapes and end sill height 5 cm	
4.4	Observed hydraulic jump parameters and energy dissipation for different discharges using selected heights of rectangular end sill	
4.5	Observed hydraulic jump parameters and energy dissipation for different discharges using selected heights of triangular end sill	
4.6	Observed hydraulic jump parameters and energy dissipation for different discharges using selected heights of semi-circular end sill	
4.7	Observed hydraulic jump parameters and energy dissipation for different discharges using selected heights of diagonal vertical upstream end sill	
4.8	Observed hydraulic jump parameters and energy dissipation for different discharges using selected heights of diagonal vertical downstream end sill	
4.9	Observed hydraulic jump parameters and energy dissipation for different shapes and sizes of end sill at a discharge of 1.65 lit/sec	
4.10	Observed hydraulic jump parameters and energy dissipation for different shapes and sizes of end sill at a discharge of 4.4 lit/sec	
4.11	Observed hydraulic jump parameters and energy dissipation for different shapes and sizes of end sill at a discharge of 4.9 lit/sec	
4.12	Observed hydraulic jump parameters and energy dissipation for different shapes and sizes of end sill at a discharge of 5.5 lit/sec	

LIST OF FIGURES

FIG. NO	TITLE	PAGE NO
3.1	Line diagram of experiment set-up	
3.2	Isometric view of inclined spillway with SAF stilling basin	
3.3	Line diagram showing different shapes of end sill	
4.1	Total energy dissipation for different shapes of end sill at selected discharges and heights of end sill	
4.2	Total energy dissipation for rectangular, triangular and semi-circular end sills at selected discharges and heights of end sill	
4.3	Total energy dissipation for diagonal vertical upstream and diagonal vertical downstream end sill at selected discharges and heights of end sill	
4.4	Hydraulic jump efficiency for different shapes of end sill at selected discharges and heights of end sill	
4.5	Hydraulic jump efficiency for rectangular, triangular and semi-circular end sills at selected discharges and heights of end sill	
4.6	Hydraulic jump efficiency for diagonal vertical upstream and diagonal vertical downstream end sills at selected discharges and heights of end sill	
4.7	Relative loss of energy for different shapes of end sill at selected discharges and height of end sill	
4.8	Relative loss for rectangular, triangular and semi-circular end sills at selected discharges and heights of end sill	
4.9	Relative loss for diagonal vertical upstream and diagonal vertical downstream end sills at selected discharges and heights of end sill	
4.10	Height of jump for different shapes of end sill at selected discharges and heights of end sill	

LIST OF PLATES

PLATE NO	TITLE	PAGE NO
3.1	Rectangular and triangular end sill with selected heights	
3.2	Semi-circular and diagonal vertical upstream end sill with selected heights	
3.3	Diagonal vertical downstream end sill with selected heights	
3.4	Laboratory experimental set-up	

LIST OF SYMBOLS AND ABBREVIATIONS

%	=	Percent
ΔE	=	Total amount of energy dissipation in SAF stilling basin
cm	=	Centimetre
d_1	=	Flow depth before jump
d_o	=	Depth of flow at outlet
d_i	=	Depth of flow at inlet
E_1	=	Flow energy before the jump
E_o	=	Total energy at outlet section
E_i	=	Total energy at inlet section
Fr	=	Froude number
Fig.	=	Figure
G	=	Gravitational acceleration
H	=	Height of end sill
H _j	=	Height of jump
J.E	=	Hydraulic jump efficiency
Lit	=	Liter
Q	=	Total discharge
R_L	=	Relative loss of energy
sec	=	Second
V_e	=	Volume of emptied part of storage tank
V_i	=	Flow velocity at inlet section
V_o	=	Flow velocity at outlet section
Z_i	=	Position head above the datum at inlet
Z_o	=	Position head above the datum at outlet
RES	=	Rectangular end sill
TES	=	Triangular end sill
SCES	=	Semi-circular end sill
DVUES	=	Diagonal vertical upstream end sill
DVDES	=	Diagonal vertical downstream end sill



Introduction

Soil erosion is one of the most serious forms of land degradation of the world (Nanna, 1996; Sohan and Lal, 2001). More than 56% of land degradation is caused by soil erosion, raising a global concern on land productivity (Elirehema, 2001). Land, water and environment are basic natural resources, essential for the sustenance of life on the earth. Unscientific and indiscriminate over-exploitation and lack of general concern towards conservation of these resources remain a serious cause of concern for soil conservationists and environmentalist's world over and it is needed to be addressed on a priority basis. Soil and water being finite and functionally non-renewable natural resources of land and water need due importance, in the overall planning process and management. The status of natural resource wealth is a strong bench mark to decide the health and prosperity of a nation. Thus, the available natural resource wealth needs to be judiciously utilized and developed further so that it remains available for long-term sustainability. In hilly regions where land slope is steep, the flow acquires accelerated velocity as it travels down the slope and consequently becomes highly erosive in nature. In order to check erosion of soil in that area, the flow parameters are required to be confined to the non-erosive range by dissipating the flow energy.

Changes in land use due to urbanization, intensive agricultural activities, poor or inappropriate supporting management practices and monoculture productions lead to accelerated soil erosion which proves to be a detrimental process both on-site and off-site. Soil erosion not only depletes soil depth, but also reduces the capacity of soil to hold water due to sealing, and affects adversely the available plant nutrients in the soil. This reduces soil productivity and causes long term reduction in crop yields (Nanna, 1996), as the necessary plant nutrients are washed away. It has been estimated that due to erosion problems crop, production is becoming uneconomical on about 20 million hectares of land annually (Elirehema, 2001). This raises concern about the ability of land to feed the ever-increasing population. Moreover, water erosion also creates offsite environmental problems, such as water pollution, siltation of reservoirs and degradation of coastal ecosystems.

The use of gradient controlling structures also known as drop structures like straight drop spillways and chute spillways is very common for safe disposal of runoff water. The basic components of inclined spillway, used as permanent gully control structures are the

inlet section, steep sloping channel section and the outlet section. Water enters the structure through the inlet and is conveyed through channel and leaves the structure through the outlet. When water passes through the steep sloping channel section, it acquires a very high flow velocity which results in a very high kinetic energy of flow. The flow in supercritical energy range from the channel section, if allowed to pass to downstream channels without any intervention at the outlet will cause very serious damages (erosion) in downstream areas. As a preventive measure, this flow in its supercritical condition is passed through a stilling basin at in the outlet, designed to dissipate the kinetic energy of flowing water by convert in to sub-critical range of energy, so that the water leaving the structure does not cause much erosion in downstream areas. Design stilling basins, also called as energy dissipaters, need high technical skill so that are more effective in causes loss of hydraulic energy, which infect is the difference in the incoming flow energy and the outgoing flow energy. These stilling basins are of various types' viz. SAF stilling basin, USBR-II stilling basin, USBR-III stilling basin, baffled stilling basin and are instated as per the required conditions at a particular place. The hydraulic energy dissipation in these stilling basins is accomplished mainly by creating of turbulence through the formation of a hydraulic jump. The high velocity flow from channel section when enters a level floor of stilling basin where it meets a stream with low flow velocity a hydraulic jump is created. To create turbulence stilling basins are provided with appurtenances in the form of chute blocks, floor blocks and end sill. These appurtenances or accessories also help to stabilize hydraulic jump in the stilling basin.

End sills are either vertical, stepped, sloped or dentate/solid wall placed at the downstream end of the stilling basin. It plays an important role in the design of stilling basins to reduce the length of jump and to improve the flow pattern at the downstream of the channel. Its main function is to reduce the length of the hydraulic jump and to control scour in large basins that are designed to reduce high incoming velocities. The end sill is usually dentate to perform an additional function of diffusing the residual portion of the high velocity jet that may reach the end of the SAF Stilling basin. The end sill, also helps in deflecting the bottom currents upward and away from the stream bed. In addition, a ground roller is created under the deflected stream, which brings bed material from downstream and deposits it at the end of the stilling basin. The effect of end sill on the flow and scour characteristics depends upon the configuration of the end sill, the end sill

geometry and the flow regime. The end sill height, configuration and position have great impact on the formation and control of hydraulic jump and ultimately leading to the dissipation of energy of flowing water and also to optimize the hydraulic jump length.

In the light of above, in this study, an attempt has been made to study energy dissipation performance of SAF stilling basins by using different combinations of selected shapes and sizes of end sill for different discharge conditions. The present work deals with a study on hydraulic jump in stilling basin with different shapes such as, rectangular, triangular, semicircular, diagonal vertical upstream and diagonal vertical downstream of different sizes and to observe flow parameters and compare their efficacy in reducing the out flow velocity and hydraulic energy dissipation. The study was conducted under laboratory conditions on simulated models with following as the broad objectives.

Objectives

- i. To observe hydraulic energy dissipation behavior in a SAF Stilling basin using different shapes of end sill of a particular height for varying discharge
- ii. To observe hydraulic energy dissipation behavior in a SAF stilling basin for a particular shape of end sill of selected heights with varying discharge
- iii. To analyse and compare hydraulic energy dissipation performance of SAF stilling basin for various combinations of shape and height of end sill with varying discharge



Review of Literature

This chapter presents a brief review of the studies conducted on the energy dissipation behaviours aspects over inclined spillway. The inclined spillway finds its extensive applications in hydraulic and environmental engineering, which is used to dissipate the energy of released flood and also to be landscape structure. Flow over the inclined spillway and the final end sill is an important and complicated hydraulic phenomena. Many researchers have concentrated on experimental research of hydraulic characteristics of the flow over the inclined spillway attached with end sill. Not much work has so far been reported on the subject, however, survey of the available literature revealed the following details.

Bradley and Peterka (1957) developed impact type stilling basins. In this study it is found that the energy dissipation is not dependent on tail water depth, but the performance of stilling basin can be improved with a moderate depth of tail water. This study resulted with the development of a new stilling basin which carries higher discharge through constructing the multiple units. Authors also advocated that new stilling basin has restraint up to discharge of 10m³/s and velocity up to 9m/s.

Chow (1959) reported a relationship for a horizontal rectangular channel, involving the sequent depth, the Froude number (F_r) and the total energy loss (ΔE) in the hydraulic jump, depth of flow before the jump (d_1) and depth of flow after the jump (d_2). He derived the relationship using the momentum principle. The relation is given as,

$$\frac{d_2}{d_1} = \frac{1}{2} \left[\sqrt{1 + 8F_r^2} - 1 \right]$$

$$\Delta E = E_1 - E_2 = \frac{(d_2 - d_1)^3}{4d_1 d_2}$$

Rand (1965) presented his work describing flow over a vertical sill in an open channel. The author emphasized that practical engineering applications are handicapped if either the relationship between the recommended design and the physical appearance of the flow is not comprehended or if one cannot predict the changes in the flow pattern of design modification.

Tung and Mayas (1982) developed a model for use in determining the optimal dimensions of stilling basin for over flow dam spillways and there appurtenances that would minimize cost and satisfy hydraulic performance of stilling basin and second phase is to use the first phase result to minimize the cost satisfying required basin performances.

Wood *et al.* (1983) reported that the stepped spillway have becomes a popular method for handling flood releases. The steps significantly increase in the rate of energy dissipation taking place on the spillway face and reduce the size of the required downstream energy dissipation basin. The compatibility of step spillways with roller compacted concrete and gabion construction technique results in low additional cost for the spillway. This paper presented a review of recent developments for the design of stepped spillway, provides a discussion of the effect of air entrainment, and present new calculation methods that take in to account the effect of flow aeration on the flow characteristics and the rate of energy dissipation.

Hager (1985) studied that the hydraulic jump in a stilling basin with an abrupt rise of the channel bottom by an elementary hydraulic approach. The results of his analysis included an expression for the sequent flow depth, the head loss due to the hydraulic jump formation and the length characteristics in term on inflow Froude number and the step height. He concluded that for a given energy head and Froude number at the upstream zone of the stilling basin, the dissipated energy was independent of the step height and cross ponds to the value of a hydraulic jump on a horizontal bottom.

Sorensen (1985) conducted a physical hydraulic model investigation to evaluate the performance of a stepped overflow spillway. The investigation demonstrated that the stepped spillway is quite effective at dissipating energy and that smooth flow transition from the spillway crest to the stepped face easily achieved. He also reported that an ogee spillway with stepped face be design to perform satisfactorily for the full range of discharges encountered by the spillway. A stepped spillway energy dissipation characteristics are comparable to those of an unstopped spillway with hydraulic jump stilling basin at the toe.

Hager (1986) reported the formation of hydraulic jump in rectangular channel, horizontal and non-prismatic channel. He made distinction between the cases in flow was separated and non-separated from channel side wall respectively. His result includes a

rational prediction of the sequent depth ratio, the relative energy dissipation and the length characteristics of the roller and jump.

Hoffmans and Pilarczyk (1995) conducted a study on local scour under time varying flow conditions. A modelling approach is presented to predict local scour time varying flow condition. The approach is validated using experimental data of unsteady scour at bed sill. The model is based on number of hypothesis concerning the characteristics of the flow hydrograph, the temporal evaluation of the scour and the geometry of the scour hole. A key assumption is that, at any time, the scour depth evolves at the same rate as in an equivalent steady flow. The assumption is supported by existing evidence of geometrical affinity and similarity of scour holes formed under different steady hydraulic conditions. Experimental data are presented that show the scour hole development downstream of bed sill due to flood hydrographs follows a predicted pattern. Numerical indicates good correspondence, especially in the rising limb of the flow hydrograph. This suggests that the underlying assumption used in the modelling approach are appropriate. In principle, the approach is general and can be applied to a wide range of environments (e.g. bed sill, step-pool provided appropriate scaling information is available, and the scour response to steady flow conditions can be estimated system) in which scouring at rapid bed elevation changes caused by time varying flows occurs, simulations are performed with the same input parameters used in the experimental tests but with no post-simulation calibration. Comparison between the experimental and model results

Garde and Saraf (1986) designed the energy dissipaters centered on the principle that the jet is made to spread over the width of stilling basin and then made to fragmented into number of smaller jets which further diffuse, thereby dissipation of energy takes place in the shortest possible length. The energy dissipater involved has been acclaimed for circular outlets whose invert level is proximate the river bed into which it is discharging.

Pillai and Goel (1989) used the wedge shaped splitter blocks having a vertex angle of 150° in the stilling basin for pipe outlets. This splitter block found to be very effective in spreading the jet of water over the width of the stilling basin within a shorter length and has better energy dissipation. They also found that the performance of the stilling basin improves by using rounded end sill instead of rectangular or sloping one.

Kumar et al. (2001) evaluated the performance of commonly used energy dissipators under laboratory conditions in terms of amount of energy dissipated and

downstream soil erosion rate. They round that USBR 3rd stilling basin gives better performance on the basin of energy dissipating characteristics, while SAF stilling basin gives lower rate of soil erosion. But they did not find any correlation between jump efficiency and downstream soil erosion rate

Noshi *et al.* (1998) reported that in case of steady jump, oscillating jump and weak jump. The end-sill reduces the maximum velocity values near the bed to about 0.40 times its corresponding value if no end-sill is constructed. However the case of undular jump, the end-sill reduces the maximum velocity values near the bed to also about 0.30 times its value if no end-sill is constructed. The different heights of end-sill resulted in approximately equal energy dissipation effect. The smallest end-sill height used of about 0.15 times the tail water depth is there for found to be sufficient to improve the energy dissipation near the bed. This indicates that increasing the height of the end sill above that sufficient height does not improve the energy dissipation efficiency any further.

Rageh (1999) studied effect of baffle block on a radial hydraulic jump (R.H.J.), with the aim to derive the limiting design parameters for this type of jump in expanding channels. The restraining design circumstances state the radial hydraulic jump, when it occurs entirely on the horizontal bed, with a sill liable to move in both vertical and horizontal directions. To obtain non-dimensional relationships between the design parameter of radial hydraulic jump for different heights of local baffle blocks this study was carried out in the laboratory for Froude number ranged from 2 to 6.5.

Chamani *et al.* (1999) conducted studies on the large model flume using fiber-optical instrumentation and reported that the onset of skimming flow is a function of critical depth, chute angle and step height. Uniform mixture depth that determine the height of chute sidewall and uniform equivalent clear water depths are described in terms of roughness froude number containing unit discharge, chute angle and step height. The spillway length needed to obtain uniform flow is expressed as a function of critical depth and chute angle. The flow resistance of stepped spillway is significantly large than for smooth chutes due to the macro roughness of the steps. The friction factor for uniform aerated flow is of the order of 0.1 for typical gravity dam and embankment dam slope, whereas the effect of relative roughness as rather small. The energy dissipation characteristics of steps spillway and the designing of training walls were also discoursed. The paper aims to focus on significant finding of a research program and developed design guidance to lessen the need for individual physical model studies.

Ohtsu *et al.* (2001) presented the upper limit of the inflow Froude number for undular-jump formations in smooth rectangular channels. They found that the formation of undular jumps depends not only on the inflow Froude number but on the boundary-layer development at the toe of the jump under conditions in which the effects of the aspect ratio and the Reynolds number on the flow condition are negligible.

Chanson *et al.* (2002) presented an indirect method to measure the skimming flow depth in stepped spillways. The measured supercritical depth was compared with that deduced from the void fraction profile obtained by the optical fiber method. The results showed agreement between both methods within 10%. Considering energy dissipation, the characteristics of relative energy loss of flow was compared with drop number and flow discharge per channel width, gravitational acceleration, and total drop height. The relative energy losses strongly influenced by the drop number. They observed that when the drop number increases, the relative energy loss ratio decreased.

Bukreev (2002) presented the experimental data on typical profiles of free surface and channel bottom pressure for a supercritical over a sill. This flow is shown to have, along with the known critical depth, two other characteristic depths, one of which is at the channel exit to the atmosphere and the other determines conditions under which the disturbances propagate well upstream of the sill. The experimental data are compared with calculation results based on a mathematical model that incorporates turbulent mixing upon wave breaking.

Negm Abdel - Azim (2002) observed that scour downstream of hydraulic structures may endanger the safety of the structures if the necessary precautions are not considered during the design stage. Normally, different measures produce different effects on reducing the maximum scour depth of hydraulic structure. In this paper, the effects of different arrangements of sills inside an abruptly enlarged stilling basin are discussed. An experimental program was conducted to investigate the effects of continuous end sill, asymmetric side sills, double staggered asymmetric side sills, symmetric side sills, central sill and continuous central sill. The flow patterns were observed and the maximum scour depths were recorded. The results revealed that in most of the cases the flow patterns are asymmetric resulting in asymmetric scours. The reduction in the maximum scour depth depends on the type of arrangement of the used sill and on the flow conditions represented by Froude number. Both of the central sills with limited width and continuous central sill

improved the flow patterns towards symmetric type and yielded minimized maximum scour depth with preference to the continuous sill.

Rajaratnam (2002) experimentally studied hydraulic jumps on corrugated beds; the range of Froude numbers was 4 to 10. The (t is the height of the corrugations, and y values of the relative roughness t_1/y_1 is the initial depth of flow) were 0.50, 0.43, and 0.25. The results showed that the lengths of the jumps were about half of those on smooth beds. The dimensionless depth deficit parameter D is defined as $(y_2^* - y_2)/y_2^*$. When y_2^* is the tail water depth of a jump on a smooth bed. The results of the study showed that the dimensionless depth deficit parameter D is approximately 0.25.

Verma and Goel (2003) conducted experiments for two pipe diameters with Froude numbers ranging from 1.70 to 5.50 to develop an efficient stilling basin with the floor at the invert elevation of the pipe outlet. Experiments were conducted with the use of different appurtenances such as splitter block, impact wall, baffle block and end sills with the specific dimensions. The performance of the stilling basin were analysed by performance number which is the function of constant experimental running time and erodible material used in experiment. The experiment resulted with the comparison between the new developed stilling basin and USBR impact type VI for the pipe outlet for the defined Froude number. In this study it is also found that for the better performance the length of basin was reduced up to 25% As compared to impact type VI stilling basin.

Chinnarasri et al. (2004) concluded that using edged sills on spillway does not increase the energy dissipation or accelerate the onset of a skimming flow when compared with sill absence. They recommended that macro-rectangular roughness be used on all steps to increase the energy dissipation by 4% rather than not using rough elements and to attain the onset of a skimming flow rapidly.

Mohammed et al. (2004) employed a physical model to simulate the effect of downstream curvature of the spillway and its end sill angle on local scour at downstream. The spillway was modeled using hard teak wood while sand was used to simulate the erodible bed. A glass sided flume with a total height of 24.9 cm and width of 8.2 cm was used to simulate the channel. The downstream curvature of spillway model with different end sill angle was tested. The effects of five different end sill angles on the local scour were tested. The values of the tested angles were 100, 200, 300, 450, and 600. Data collected from the experiments conducted on the physical model showed a reduction of 15% in local scour depth at downstream when the end sill angle changed from 100 to 600.

Tokyay (2005) experimentally investigated the effect of channel bed corrugations on hydraulic jump. In the experiments, wave steepness values of 0.20 and 0.26 were used, and the range of Froude numbers was 5 to 12. The ratio of the tail water depth to the initial depth was determined as a function of the Froude number. The length of the jump and the energy dissipation in the jump were also determined. The results were compared to the data obtained with a smooth channel bed. Some investigations have recently been carried out on hydraulic jumps on corrugated beds, the information concerning the effects of corrugation on hydraulic jump characteristics is incomplete, and very few attempts have been made to study the effects of wave steepness of corrugated bed on a hydraulic jump. The objective of this research was to investigate the effect of a sinusoidal corrugated bed on the characteristics of a jump within a wide range of wave steepness values (t/s). The values of the relative roughness t/y were found to be 0.32 to 0.67, and s/y was 0.85 to 3.33.

Barani et al. (2005) investigated energy dissipation of flow over stepped spillways of different step shapes, a physical wooden model has been built in the Shaheed Bahonar University's hydraulics lab. This model with 41.41° slope has 84 cm height and 21 steps. Each step has 4 cm height, 4.5 cm width and 30 cm length. Experiments have been carried out for different types of step shapes (plain steps, end sill steps with thickness of 1, 2, 3 and 4 cm and steps with a bottom adverse slope of 15° , 26.36° and 45°). Overall, 131 experiments were done, the hydraulic parameters of flow over the model were measured and the energy dissipation of flow was calculated. Results show that the energy dissipation of flow on end sill and inclined stepped spillways are more than the plain one, it is increased by increasing the thickness of end sill or the adverse slope size. Comparison of flow energy dissipation over end sills stepped spillway and inclined type show that the inclined type has been dissipated more energy than the equivalent end sill type. Also for stepping spillway of different step shapes, flow energy dissipation decreases with increasing the flow rate. It is concluded that for a large stepped spillway with high flow rate the inclined type spillway is more effective than the other forms.

Chinnarasri (2006) reported that to reduce the size of stilling basin for energy dissipation a stepped chute has been accepted to be the most powerful hydraulic structure to dissipate large flow energy downstream from steep hills. This paper presents the flow characteristics and factors for energy dissipation in various types of stepped chutes: horizontal steps, inclined steps, and steps with end sills. Delineated and described flow

regimes are observed. The relationships between relative energy loss and relative critical flow depth on three stepped chutes are presented and discussed. The steps with end sills seem to be the most efficient configuration in terms of relative energy dissipation. The effect of number of steps is evident since the relative energy loss increases with the number of steps. In addition, new correlations showing the relation between relative energy loss and relative critical flow depth are proposed for practical applications.

Othman (2008) investigated the problem of local scour downstream of an ogee spillway and by using two type non-cohesive bed material. The paper briefly explain the effect of hydraulic condition of flow and sediment characteristics on depth and extent of scour. The obtained result show that the depth and extent of scour was greatly affected by the rate of the discharge and the depth of tail water. He also observed that the bed material particles plays an important role in the characteristic of the occurred scour. The experimental data was used to develop two empirical relations to predict the depth and the extent of the scour downstream the ogee spillway.

Frizell Warren (2009) reported that the stepped spillways operating in the skimming flow regime are well known to result in higher levels of energy dissipation than would occur on a smooth chute of equal drop. Empirical modelling and analytical methods using equivalent friction factors based on the step roughness have been successful in predicting general hydraulic characteristics such as depth and mean velocity. However, using bulk to design standard stilling basins has not always been successful, especially for stepped spillways of milder slopes. A review of previous research including new laboratory hydraulic modelling and computational fluid dynamics model data are used to gain insight to possible explanations which seem to infer that the mean energy available may not be as important as the chute slope and vertical distribution of energy entering the stilling basin.

Abbaspour (2009) studied experimentally over six corrugated beds with varying wave steepness, which had corrugation and Froude numbers in the range of 0.286 to 0.625 and 3.8e8 to 8.6, respectively. The effects of wave height and length of corrugation on the basic jump characteristics, including free surface location, velocity, shear stress distribution and energy dissipation, were studied for a range of Froude numbers. The dimensionless hydraulic parameters were found to be a function of the Froude number. The results showed that the tail water depth and the length of the jump on corrugated beds are smaller

than those of the corresponding jump on a smooth bed. The analysis of velocity profiles at different sections in the jump showed that the velocity profiles were similar to those of a simple plane wall jet. The normalized boundary layer thickness d/b was equal to 0.57 for jumps on a corrugated bed, compared to 0.16 for the simple wall jet. The analysis and comparison of the bed shear force and shear stress coefficient showed that shear stress on a corrugated bed is about 10 times that of a smooth bed. The results of this study are in good agreement with previous results and showed that corrugated beds can be used to dissipate the excess hydraulic jump energy in stilling basin.

Tiwari *et al.* (2010) experienced that the stilling basins are transition structures assembled to dissipate excess energy limited by high velocity flow at the outlet of conduit or tunnel so that the flow beyond the basin does not threaten the stability of bed and banks of downstream channel. This study indicated that, in stilling basin kinetic energy causes turbulences and it is ultimately lost as heat and sound energy. There are several types of stilling basins which are used in various hydraulic structures like dam, canal, culvert etc. This type of stilling basin most suitable at a particular location mainly depends upon initial Froude Number and initial velocity of flow. This study results with design principles and features of various stilling basins used for outlet works.

Alikhani *et al.* (2010) conducted experiments to evaluate effects of a single vertical continuous sill and its position on control of depth and length of a forced jump in stilling basin without considering tail water depth which is variable and totally controlled by downstream river conditions. A sill with five different heights was placed at three different longitudinal distances along a scaled model of a stilling basin. The hydraulic characteristics of the jump were measured and compared with the classical hydraulic jump under variable discharges. Results of experiments confirmed significant effect of the sill on dissipation of energy. A new relationship was developed between sill height and position, sequent depth ratio, and length of stilling basin. The advantage of the proposed relationship in practice is its capability to design stilling basin where tail water depth is unpredictable.

Kumar *et al.* (2010) reported that the hydraulic jump primarily serves as energy dissipater to dissipate excess energy of flowing water downstream of hydraulic structure such as spillway, sluice gates, etc. This excess energy, if left unchecked, will have adverse effect on the banks and the beds. A review of literature shown that earlier researcher concentrated more on horizontal channel while very little

information is available on sloping channels. Further they have studied the hydraulic jump characteristics only in terms of approach Froude number. In the present paper hydraulic jump in sloping channel has been studied and analysed. The results obtained were compared with the result of horizontal channel to determine the effect of slope on hydraulic jump characteristics. The empirical computational models were developed for relative length and relative energy loss considering the effect of approach Froude number and incoming Reynolds number.

Ali Abdelazim *et al.* (2010) investigated the effect of different shapes of stilling basins of regulator on the length of the submerged hydraulic jump, velocity profiles along the apron, and local scour downstream regulator floor. Extensive experimental program was conducted on a re-circulating flume with 1.0 m wide, 26.0 m long and 1.2 m deep, with discharges range from 40 to 190 l/s. The relative velocity near bed, and shear Reynolds number were studied to fix the best shape of stilling basin that could reduce both of length of submerged hydraulic jump and local scour downstream stilling basin. Statistical equation was developed to correlate the length of submerged jump with the other independent parameters. Finally, clear matching of results from the length of jump and velocity analysis was investigated.

Dermawan *et al.* (2011) presented the results of the experimental studies conducted on the residual energy and relative energy loss on the stepped spillway of 45° slope, 100 cm height, 30 cm wide, with continuous steps cut into the surface of spillway from the crest to the toe. The variations number of steps was 2, 4, 8, 16, 32 steps, and 5 variations of flow rates from 1.73 less- 1 to 6.15 for each number of steps. Graph representing the dimensionless relationship among parameters, were useful information for the hydraulic design of 1V:1H stepped spillway.

Hosseini (2011) presented the effect of a broad crested sill in forming a controlled hydraulic jump in a triangular channel. The experiments were carried out in a horizontal symmetrical triangular channel with the central angle of 94.4°. A broad crested sill was installed at the end of the classical hydraulic jump to ensure that the jump will be build up where adequate tail water is not available. The results are compared with the previous experimental and theoretical studies and empirical equations are developed by means of experimental results to predict the sequent depth ratio and the length of the jump and surface rollers.

Fathi-Moghadam (2011) conducted experiments to characterize forced hydraulic jumps in stilling basins for enforced cases due to tail water level or dam site arrangement and construction. The case with a single tall sill was simulated in a horizontal flume downstream of a sluice gate. Results of experiments are compared with the classical hydraulic jump, and significant effect of tall sill on dissipation of energy in shorter distance was confirmed. Furthermore, the generated jumps were classified based on the ratio of sill height to basin length, and a simple design criterion was proposed to estimate the basin length for a desired jump and particular inflow.

Hesham (2012) studied a two-dimensional physical model used to evaluate the effectiveness of adding baffles and sills at step edges or of shifting them from step edges of a 1V:1H sloping, short, sharp- or round-crested stepped spillway with an ogee inlet. A comparison between deferent configurations of baffles and sills was carried out with respect to the energy dissipation and the flow characteristics. The baffle-shifted round-crested spillway gives the smallest discharge required for the onset of a skimming flow among all other configurations. The baffle-edged chute dissipates more energy than the sill-edged spillway. Shifting baffles or sills from the sharp edges decreases the energy dissipation. Shifting baffles or sills from the round-crested spillway increases the energy dissipation in the range of the discharges studied. Empirical equations for energy dissipation are introduced for practical application of spillways of comparable similar conditions.

Tiwari (2013) reported a significant effect of the shape of the end sill geometry on the reduction of scour depth downstream of end sill for the pipe outlet stilling basin inspected the energy dissipation by varying the gap of baffle wall in the stilling basin to protect the downstream structures from immense scouring. Experiments were carried out for Froude number 3.85, 2.85, 1.85 with keeping the baffle wall at same location. Experiments resulted with much effect on the performance of the stilling basin by changing the gap underneath the wall from the basin floor due to change in floor pattern. During the study it was found that the flow condition as well as the scouring pattern in downstream of the stilling basin affected by the gap of impact wall in the basin. He also studied about scour pattern downstream of stilling basin for non-circular pipe outlet using end sill of different geometry. The study was conducted by designing new stilling basin models in a rectangular shaped pipe outlet with three inflow Froude numbers namely, $Fr=1.85$, 2.85 and 3.85 to study the scour pattern downstream of stilling basin.

Shahmirzad *et al.* (2014) investigated the hydraulic characteristics of an in-ground stilling basin (ISB) below a flood mitigation dam (FMD). The ISB structure is adapted to be ecologically transparent for fish migration and sediment transport through consideration of two lateral free spaces at the ISB end. We attempted to assess the energy dissipation performance of ISB by considering the interdependence between ISB geometry and flow pattern. The experimental results evidence there is a significant correlation between flow patterns and ISB geometry.

Zubaidy (2014) investigated the effects of the direction diverting blocks, (DDBs), fixed on an ogee spillway surface with different slope on energy dissipation. Three ogee spillway models were prepared with slope of 1:1, 0.85:1, and 0.75:1. All models were constructed with a scale ratio of 50:1. Six sizes of DDBs of triangular shapes were used. These blocks were arranged in eighteen for slope 1:1, fourteen configurations for each spillway models with slope 0.85:1 and 0.75:1. The configurations differ in spacing between rows of blocks and the number of rows.

Beg (2014) conducted study on hydraulic jump in stilling basin with vertical end sill. The objective of the study was to assess the effectiveness of vertical end sill and its position on control of length of stilling basin to economize the cost of stilling basin. The work was carried out based on reliable data collected from published work of various investigators on hydraulic jump in stilling basin with vertical end sill. The effectiveness of vertical end sill in reducing the length of hydraulic jump (i.e. length of stilling basin) was critically examined from the available data. The study revealed that there is a significant dissipation of energy and reduction in length of hydraulic jump due to the presence of vertical end sill. It was found that the sequent depth ratio and length of the stilling basin are greatly affected by sill height and position.

The survey of available literature on the subject revealed that some studies have been conducted to observe energy dissipation performance of a few shapes of end sill but no work has been reported to observe hydraulic energy dissipation performance with end sills of different heights. Accordingly, this study was undertaken to conduct laboratory experiments on simulated models to observe and analyse the hydraulic energy dissipation behavior of SAF stilling basin with different shapes of end sill with varying heights at different discharges. The observations were also compared to compare their performance.



Materials & Methods

This section deals with the material used and description of the various methodologies and techniques adopted in this study. It includes description of material required for the experiment, installation of experimental setup, and the methodology used for recording observation as per the mandate of the study. The detailed description is given under in the following subsections.

3.1 Description of Materials Used

3.1.1 An inclined spillway

To conduct experimentation, an inclined spillway with SAF stilling basin was used. An inclined spillway is a structure in which all or a part of the energy is dissipated. An inclined spillway, designed for a total drop of 63 cm and for design discharges of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec installed in the Department of Soil and Water Conservation Engineering laboratory was used for this study. A line diagram of the inclined spillway along with SAF stilling basin is shown in Fig 3.1. The spillway has a rectangular inlet section of 10cm x 12.5cm x 22cm size, a 190 cm long steep sloping channel section and a 132 cm long outlet section in the form of a SAF stilling basin. It is fabricated by using an approximately 3 mm thick metallic sheet. Water enters the structure through the inlet section is conveyed through the channel and leaves the structure through the outlet. When water passes through the steep sloping channel section, it acquires a very high flow velocity which results in a very high kinetic energy of flow. As a preventive measure, this flow which is in its supercritical condition, is passed through the stilling basin at the outlet. The outlet is designed for dissipating the kinetic energy of the flowing water convert in to the sub-critical range of energy, so that the water leaving the structure does not cause much erosion in the downstream areas.

3.1.2 SAF stilling basin

Stilling basins, also called as energy dissipaters, need high technical skill in its design so as to make them more effective in terms of loss of hydraulic energy, which is the difference in incoming flow energy and out going flow energy. These stilling basins are of various types viz. SAF stilling basin, USBR-II stilling basin, USBR-III stilling basin, baffled stilling basin and are employed as per the existing conditions at a place.

In this study, a SAF stilling basin was used for conducting experimentation with different shapes and sizes of the end sill (Fig 3.1). The hydraulic energy dissipation in these stilling basins is accomplished mainly by way of turbulence created through the formation of a hydraulic jump. The high velocity flow from the channel section, when enters a level floor of the stilling basin where it meets a stream with low flow velocity, a hydraulic jump is created.

3.1.3 Chute Blocks and floor blocks

To create turbulence, stilling basins are provided with appurtenances in the form of chute blocks, floor blocks and end sill. These appurtenances or accessories also help to stabilize hydraulic jump in a stilling basin. The chute blocks, located at the entrance of the stilling basin, serve to increase the effective depth of the entering stream, break the stream up into a number of small jets, and help create the turbulence required for effective energy dissipation. Similarly, the floor blocks located on the floor of the horizontal floor of the stilling basin help in creating turbulence and energy dissipation. It makes no difference in the performance of the stilling basin whether a chute block or a space is next to the sidewall as long as the blocks are symmetrical about the centreline of the outlet.

If the distance between the chute and floor blocks is too short, the blocks act like a solid block. If the distance between the floor blocks and the end sill is too short, the blocks and sill act as a unit in deflecting the jet upward. The width and spacing of the floor blocks should be the same as for the chute blocks. However, for those stilling basins in which the sidewalls diverge in plan, the width and spacing of the floor blocks should be increased over the chute block width and spacing to compensate for the greater stilling basin width at the floor block location. Insufficient water can pass between the floor blocks if they occupy too much of the stilling basin width; they then act more like a sill than like individual blocks. The aggregate width of all floor blocks, therefore, should be held within these limits, even if it is necessary to reduce the width of the floor blocks to do so. The floor blocks always should be placed downstream from the openings in the chute blocks to break up the jets issuing from between the chute blocks and passing along the stilling basin floor.

3.1.4 End Sill

End sill may be described as a vertical, stepped, sloped or dentate/solid wall at the downstream end of the stilling basin. End sill plays an important role in the design of a stilling

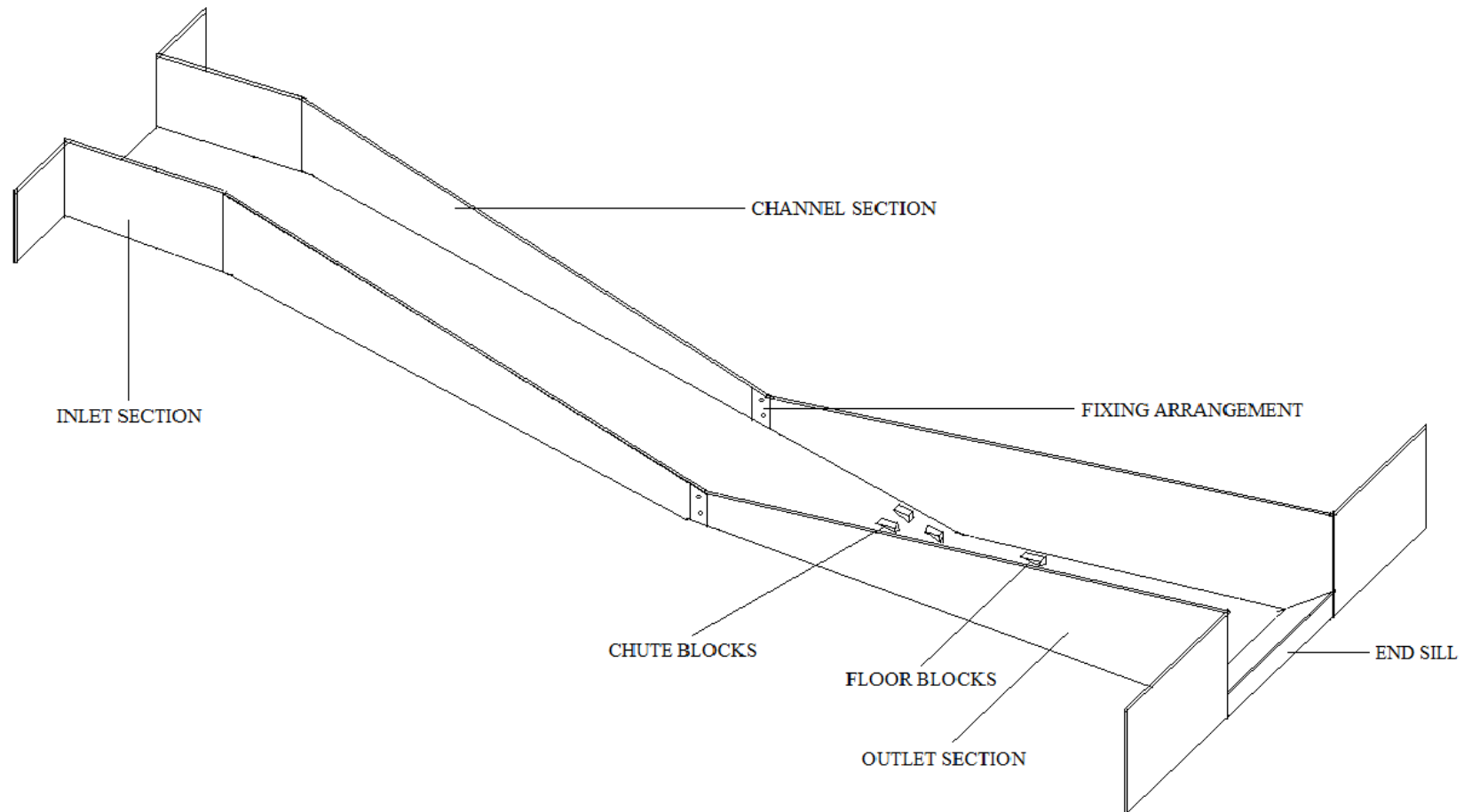


Fig. 3.2 Isometric view of inclined spillway with S.A.F. stilling basin

basin for reducing the length and also helps in improving the flow pattern at downstream of the channel. The effect of end sill on the flow and or scour characteristics depends on the configuration of the end sill, the end sill geometry and the flow regime. The end sill height, configuration and position have a great impact on the formation and control of hydraulic jump and ultimately leading to the dissipation of energy of flowing water, and also to optimize the hydraulic jump length. The present work deals with a study on the hydraulic jump in the stilling basin with different shapes such as, rectangular, triangular, semicircular, diagonal vertical upstream and diagonal vertical downstream of different sizes, and to observe the flow parameters and compare their efficacy in reducing the out flow velocity and hydraulic energy dissipation.

The end sill is constructed at the downstream end of a SAF stilling basin. Its function is to reduce the length of the hydraulic jump and to control scour in large basins, which are designed for reduction in high incoming velocities. The end sill is usually dentate to perform an additional function of diffusing the residual portion of the high velocity jet that may reach the end of the SAF Stilling basin. The end sill, located at the downstream end of the stilling basin, deflects the bottom currents upward and away from the stream bed. In addition, a ground roller is created under the deflected stream, which brings bed material from downstream and deposits it at the end of the stilling basin. Dentate end sill of different shapes and sizes were used in the SAF stilling basin. These were rectangular end sill (RES), triangular end sill (TES), semi-circular end sill (SCES), diagonal vertical upstream end sill (DVUES) and vertical diagonal downstream end sill (DVDES) for 3 cm, 4 cm, and 5 cm end sill heights. These end sills were fabricated at the Farm Machinery and Power Engineering work shop, GBPUA&T, Pantnagar. In total, 15 different models were fabricated to conduct the experimentation. These fabricated models of end sills with different shapes and sizes are shown in Plate 3.1 to Plate 3.3.

3.1.5 Water storage tank

Source of water to conduct experiments was the water supply line which supplies water to an overhead tank on the roof of Irrigation and Drainage Engineering Laboratory. The water from this supply line was collected in a storage tank, having dimension 2m x 2m x 1.5m (capacity 6000 lit) located near the experimentation site. The water from the overhead source was conveyed to the storage tank by a flexible pipe line and was left open till the storage tank got filled.

3.1.6 Water delivery and circulation system

Water was made to flow from the reservoir end of connecting pipe with the help of a centrifugal pump. The foot valve of the connecting pipe was placed in to the reservoir. A gate valve was attached to the connecting pipe to regulate the discharge of water to the storage tank. The arrangements were made in such a way that the outflow from the spillway (stilling basin) comes back to the storage tank. This was done to circulate water for conducting experimentation and the time required to fill the storage tank is saved, and also to eliminate any wastage of water.

3.1.7 Discharge regulation system

The desired rate of water supply was maintained with the help of a regulatory valve fixed in the delivery pipe. The water was supplied at four selected discharge rates of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec. and 5.5 lit/sec to conduct experimentation. This discharge was obtained by calculating the controlled valve through physical measurement. The excess water pumped in to the delivery line come back to the storage tank by way of a by pass line.

3.1.8 Centrifugal pump

A 3 hp centrifugal pump assembly was used to lift water from the underground storage tank and supply it to the SAF stilling basin to conduct experimentation. The pump received power from an electric motor. The supply from the pump was regulated by a regulatory valve to ensure the required rate of water supply.

3.1.9 Hook gauge/point gauge

The water level in the inlet and outlet sections of the SAF stilling basin was observed with the help of field type point or a hook gauge. Sometime fixed and ordinary plastic scale was also used, but for accurate work a point gauge or hook gauge gives better recording.

3.1.10 Measuring cylinder

Graduated measuring cylinder of 1000 ml and 500 ml capacities were used to measure the volume of water to calibrate the rate of discharge from the centrifugal pump. These cylinders were obtained from the Soil and Water Conservation Engineering laboratory.

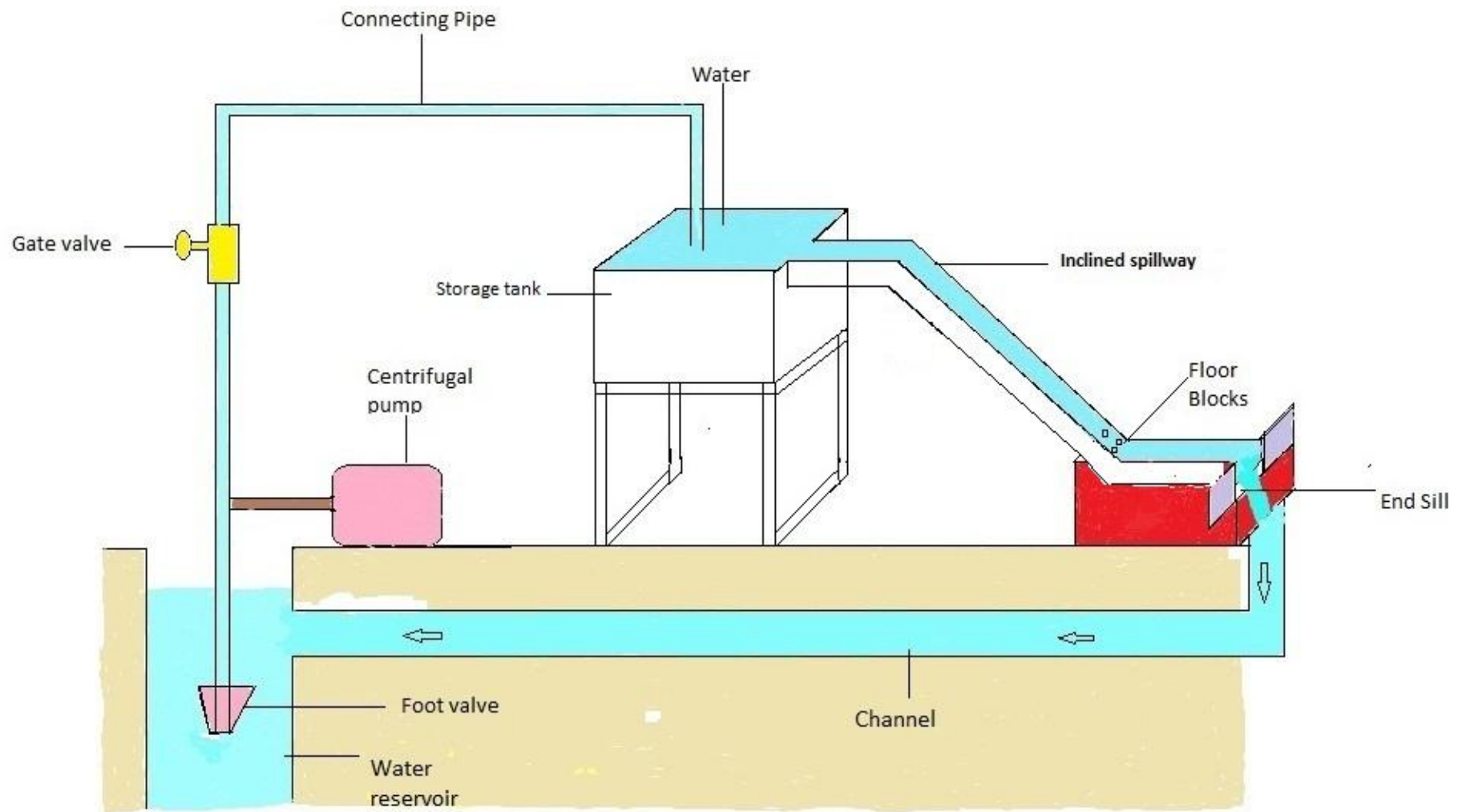


Fig. 3.2 Line diagram of experimental set-up

3.1.11 Stop watch

A stop watch was used to note the timing of observation recorded during water filling in the tank. A time of 10 second was kept to observe the water level in the storage tank.

3.2 Methodology Adopted

3.2.1 Fabrication of end sills of different shapes and heights

The end sill is usually dentate to perform an additional function of diffusing the residual portion of the high velocity jet that may reach the end of the SAF Stilling basin. The end sill height, configuration and position have great impact on the formation and control of hydraulic jump and ultimately leading to the dissipation of energy of flowing water and also to optimize the hydraulic jump length. In the present study, end sills with following shapes were used.

- i. Rectangular end sill (RES)
- ii. Triangular end sill (TES)
- iii. Semicircular end sill (SCES)
- iv. Diagonal vertical upstream end sill (DVUES)
- v. Diagonal vertical downstream end sill (DVDES)

The end sills of the above shapes were fabricated with heights of 3 cm, 4 cm and 5 cm with a base width of 4.0 cm and 10 cm length. The fabrication was done with an iron plate of 5mm thickness in the workshop of Farm Machinery and Power Engineering GBPUA&T, Pantnagar. For each shape of the end sill, 3 models of different heights of 3 cm, 4 cm and 5 cm were fabricated. In this way for five different shapes of end sill a total 15 number of models were fabricated. The design dimensions of these end sills are shown in Fig 3.2 and the fabricated models are shown in Plate 3.1 to Plate 3.3.

3.2.2 Development of experimental set-up

To conduct experiments, the experimental set-up was installed in the Hydrologic Simulation and Sedimentation Laboratory which is near to Soil and Water Conservation Engineering Laboratory. The complete installation consisted of mainly the controlled water supply system, storage tank, inclined spillway with SAF stilling basin, and a by-pass line. The inclined spillway attached with the SAF stilling basin was installed at a drop of 63 cm. The model structure was installed on a metallic reservoir tank which receive the water supply through a water circulatory system. The details of various components of the experimental set-up is shown in Fig. 3.2.

3.2.2.1 Assembling of water supply line

To obtain proper water supply for experimentation, a leak proof water supply line using flexible pipes was assembled using different sizes of pipes, elbows and reducer. The joints were clamped by using rubber gaskets to make them leak proof with proper assembly so that a smooth trouble free water supply is obtained. Firstly, a two inch suction pipe was connected with inlet of the pump and other end was connected with the foot valve. The delivery from the pump was taken to the testing structure through a regulation valve.

3.2.2.2 Installation of inlet to source tank

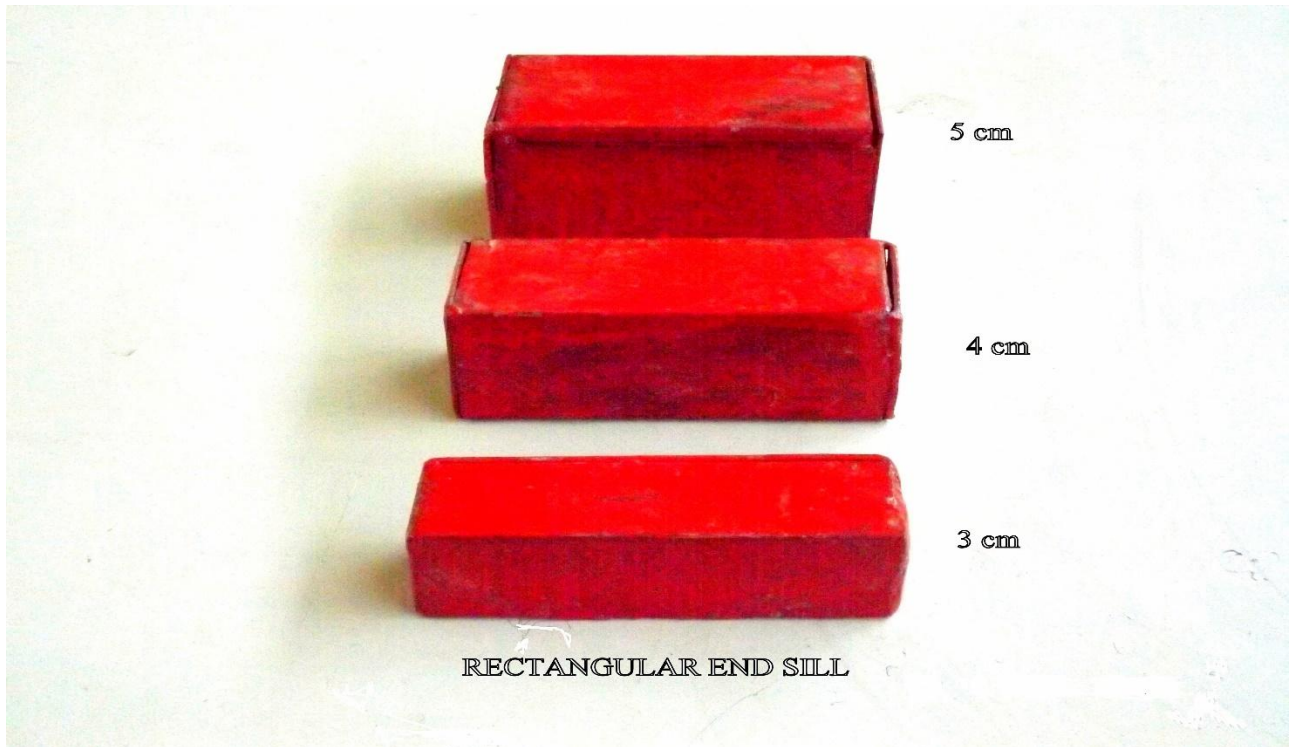
The water was delivered to the source tank, rather than directly flowing it over the end sill with the attached SAF stilling basin to reduce the effect of turbulence and approach velocity of the incoming water from the pumps. A rectangular SAF stilling basin was attached with different shapes and sizes of end sill. The different shapes and sizes of end sills were fabricated at the farm machinery and power engineering workshop.

3.2.2.3 Fixing SAF stilling basin with delivery tank

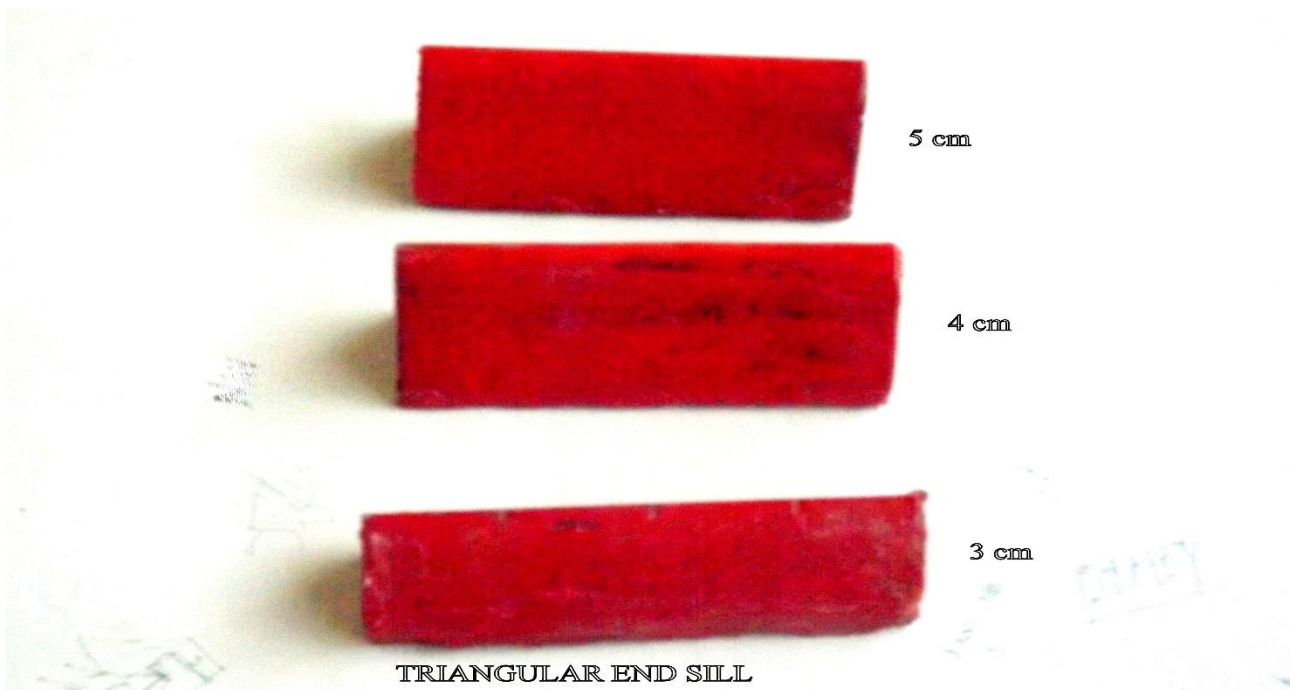
After the delivery tank was set-up at a constant height, the SAF stilling basin was attached with the front side of the delivery tank. The attachment between SAF stilling basin and the delivery tank was done with the help of wall putty. The end sill was attached with the help of m-seal in SAF stilling basin. This procedure was repeated every time when the end sill was required to attach with the end of the SAF stilling basin. In the present study, five shapes and three heights of end sills with the same drop were used.

3.2.2.4 Fixing different shape and size of end sill

The different shapes and sizes of end sills were fixed one by one with the SAF stilling basin. At first the rectangular shape of end sill at selected heights of 3 cm, 4 cm and 5cm were fixed with the help of m-seal in the SAF stilling basin for selected discharges of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively, and observations were recorded for the flow depth at inlet and outlet sections. Then the triangular shaped end sill for the selected heights were fixed with the help of m-seal in the SAF stilling basin. Similar procedure was adopted to fix remaining shapes (semi-circular, diagonal vertical upstream, diagonal vertical downstream) end sills. In fact, to test 15 different end sills for their energy dissipation performance, 15 models of



(a)



(b)

Plate 3.1 Rectangular and triangular end sill with selected heights

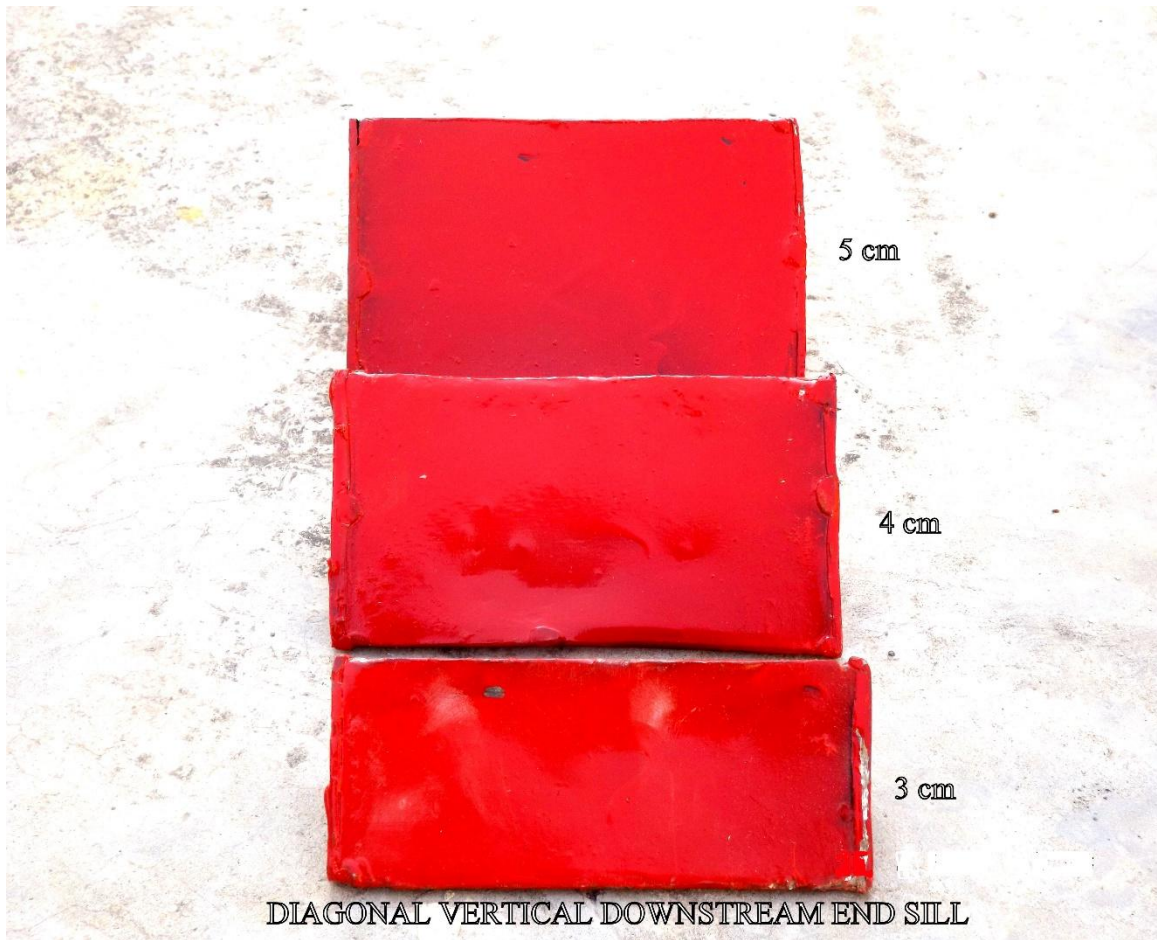


(c)



(d)

Plate 3.2 Semi-circular and diagonal vertical upstream end sill with selected heights



(e)

Plate 3.3 Diagonal vertical downstream end sill with selected heights

inclined spillway were required. To avoid huge fabrication needed to fabricate these models of inclined spillway, the end sills were fixed one by one in the common spillway (Stilling basin) for experimentation. While fixing every time care was taken to make the fixing leak proof.

3.2.2.5 Filling of storage tank

A water storage tank having approximate dimensions as 2m x 2m x1.5m was used as the source of water which was filled completely. The water was taken from a tap through pipes. One end of the pipe was attached to the tap and the other end was put to the storage tank. The source of water was shut down when the tank was filled completely. Then this water was carried to the delivery tank with the help of a centrifugal pump driven with an electric motor.

3.2.2.6 Regulation of discharge

To find the effect of size and shape of end sill, experiment was required to be conducted at a specified discharge. In order to obtain the desired discharge, supply from these pumps was regulated through a regulating valve fitted on the delivery pipe. When the required discharge become available, the experiment is completed. Then again, through the water regulated system another discharge was obtained and the experiment was carried out in a similar way. In this way, water regulation was carried out four times to obtain these specified discharges. The volumetric method was adopted to measure discharge from the pump. In this method the water from the pump was collected in a collection tank for a specified duration.

The flow obtained by the centrifugal pump was calibrated to obtain the desired rate of discharge. For this purpose, the circular handle of gate valve was marked at a point after tightening it. Storage tank was filled with water up to the base of spillway connected with it and the time taken to fill the storage tank up to that height was noted down. The volume of water was calculated by using the formula:

$$V_p = L * B * D \quad \dots (3.1)$$

where,

L = length of the storage tank

B = breadth of storage tank

D = depth of water pumped out from storage tank

V_p = volume of water pumped out

3.2.3 Experimentation and observation

3.2.3.1 Recording of hydraulic jump parameters

Once the experimental set up was ready and the required discharge was available experimentation was started. When hydraulic jump formation got stabilised in the stilling basin for particular set of conditions, observations were recorded. The flow depths at the inlet and outlet were observed to obtain the hydraulic jump parameters, such as flow energy at inlet, flow energy at outlet, total energy loss, hydraulic jump efficiency, and relative loss of energy and height of jump. The procedure was repeated every time for different conditions of end sill shape, size and discharge.

3.2.3.2 Determination of hydraulic energy dissipation

The difference in the total flow energy at the inlet (E_i) of the test structure and at the outlet (E_o) of the test structure gives the total amount of energy dissipated (ΔE) between the two section. The total energy of flow comprises of the sum of position head, pressure head and velocity head at a point can be shown as below.

$$\Delta E = E_i - E_o \quad \dots(3.2)$$

$$E_i = Z_i + d_i + \frac{V_i^2}{2g} \quad \dots(3.3)$$

$$E_o = Z_o + d_o + \frac{V_o^2}{2g} \quad \dots(3.4)$$

where, (Z) is the position head above a datum, (d) is the depth of flow. (V) is the velocity of flow, (g) is the gravitational acceleration. The suffix (i) and (o) denote inlet and outlet section respectively. The flow velocity before and after jump was determine to the delivery discharge with the cross-sectional area of the channel.

3.2.3.3 Determination of hydraulic jump efficiency and relative loss

The hydraulic jump efficiency is the ratio of total flow energy at the outlet (E_o) of the test structure and total flow energy at the inlet (E_i) of the test structure. The hydraulic jump efficiency can be calculated by using the formula:

$$JE = (E_o/E_i) \times 100 \quad \dots(3.5)$$

The value of jump efficiency is the least when for a given amount of inflow energy (E_i), the value of outflow energy (E_o) is minimum. It means, the jump efficiency is minimum when the total amount of energy dissipation is maximum i.e., at the end sill, maximum energy dissipation will be the least efficient in terms of jump efficiency



Plate 3.4 Laboratory experimental set-up

The relative loss on the other hand provides a realistic information about the performance of a stilling basin. It is the ratio of the amount of energy dissipated to the incoming flow energy, and is represented as,

$$R_L = \frac{E_i - E_o}{E_i} \times 100 \quad \dots (3.6)$$

It means the relative loss is maximum when the total amount of energy dissipation is maximum. i.e., an end sill resulting in maximum energy dissipation will be the most efficient in terms of relative loss.

3.3 Analysis of Observed Data

To determine the flow velocity at a point, the depth of flow was measured and the discharge was then divided by the known depth of flow. Then with the known flow velocity the value of incoming and outgoing Froude number were calculated by using the following relationship.

$$F_r = \frac{v}{\sqrt{gd}} \quad \dots (3.7)$$

The depth of flow in jump (d_2) and depth of flow before the jump (d_1) were obtained by using the jump formula as shown below.

$$d_2 = \frac{d_1}{2} \left[\sqrt{(1 + 8Fr_1^2)} - 1 \right] \quad \dots (3.8)$$

The experimentation were conducted for various condition of input variables like end sill size, shape and discharge. Observation were recorded and analysed as per the mandate of the study.



Results & Discussion

As per the objectives of this study, experiments were conducted to observe hydraulic energy dissipation behaviour through the formation of hydraulic jump in an inclined spillway using SAF stilling basin. The observation were recorded using different shapes of end sill such as rectangular end sill (RES), triangular end sill (TES), semi-circular end sill (SCES), diagonal vertical upstream end sill (DVUES) and diagonal vertical downstream end sill (DVDES) with different heights for a range of selected discharges. In all experiments, the total drop was kept constant at 63 cm. The observations were recorded and the calculated, Energy dissipation behaviour was compared for different combinations of end sill shapes, its height and discharge and are presented in following sections.

4.1 Hydraulic Energy Dissipation Behaviours Using Different Shapes for a Particular Heights of End Sill at Selected Discharges

The hydraulic energy dissipation behaviour using different shapes such as rectangular end sill (RES), triangular end sill (TES), semi-circular end sill (SCES), diagonal vertical upstream end sill (DVUES) and diagonal vertical downstream end sill (DVDES) for a particular height of end sill (3 cm, 4 cm and 5 cm) at selected discharges of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec were recorded and analysed to observed the effect of end sill shapes on hydraulic energy dissipation. The recorded observations are tabulated in Table (4.1 to 4.3) and described for the different conditions.

4.1.1 Hydraulic energy dissipation behaviour using different shapes for a 3 cm height of end sill at selected discharges

The observed values of hydraulic jump parameters presented in Table (4.1), indicate that for all selected shapes such as rectangular, triangular, semi-circular, diagonal vertical upstream and diagonal vertical downstream end sill with an end sill height of 3 cm, the energy dissipation was found to be 43.443 cm, 43.063 cm, 43.404 cm, 42.981 cm and 43.928 cm at a discharge of 1.65 lit/sec for rectangular, triangular, semi-circular, diagonal vertical upstream and diagonal vertical downstream end sills respectively. Similarly, for the discharge of 4.40 lit/sec the total energy loss was observed as 44.716 cm

for rectangular end sill and 44.927 cm for triangular end sill, while total energy dissipation was found to be 43.667 cm, 45.310 cm and 45.431 cm for semi-circular, diagonal vertical upstream and diagonal vertical downstream end sills respectively. For the selected shapes of end sill such as rectangular, triangular, semi-circular, diagonal vertical upstream and diagonal vertical downstream, the total energy loss was found to be 44.345 cm, 45.282 cm, 43.547 cm, 44.166 cm and 43.546 cm at a discharge of 4.9 lit/sec respectively. In this case the maximum energy dissipation was observed as 45.282 cm for triangular end sill at a discharge of 4.9 lit/sec. In case of discharge of 5.5 lit/sec the total energy loss was observed as 44.203 cm and 44.032 cm for rectangular and triangular end sill, while the total energy loss was found to be 43.432 cm, 43.787 cm and 43.666 cm for semi-circular, diagonal vertical upstream and diagonal vertical downstream end sill respectively.

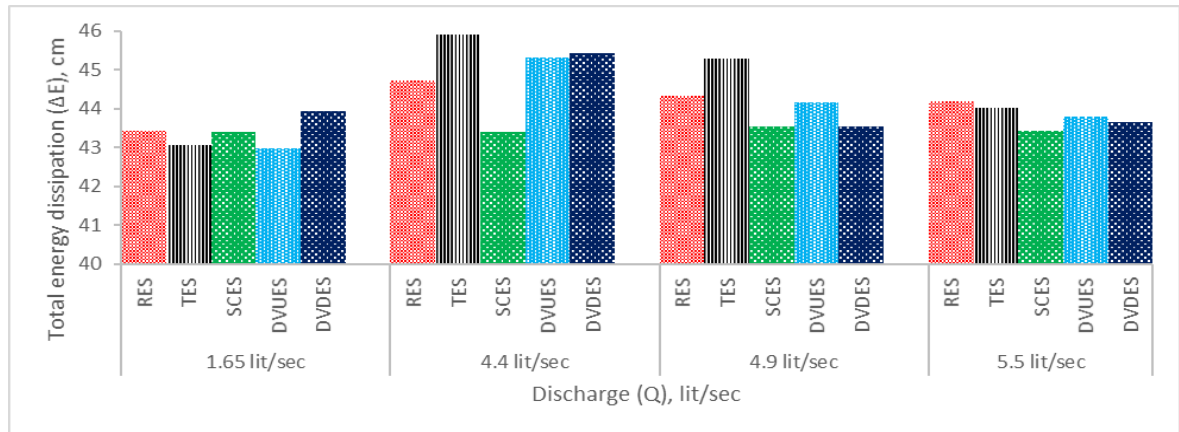
The observation recorded in Table (4.1), clearly indicate that for all selected shapes of end sill of height 3 cm the maximum amount of energy dissipation was found to be 45.927 cm at a discharge of 4.4 lit/sec for triangular end sill and minimum energy loss was found to be of 42.981 cm for diagonal vertical upstream end sill at a discharge of 1.65 lit/sec. The graphical presentation of hydraulic energy dissipation behaviour for all selected end sills with 3 cm height for all selected discharge the best performance in terms of energy dissipation was observed in case of triangular end sill as is evident from Fig. 4.1 (a).

4.1.2 Hydraulic energy dissipation behaviours using different shapes for a 4 cm height of end sill at selected discharges

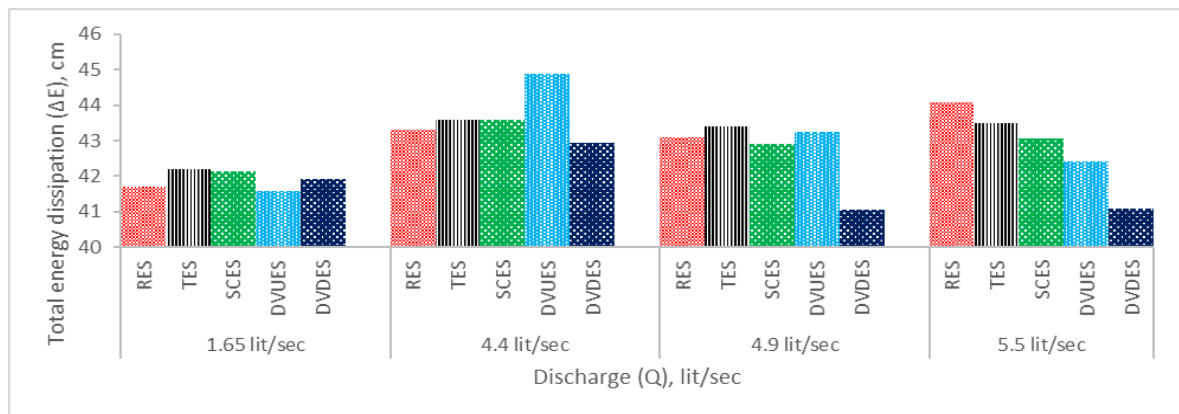
The observation of hydraulic energy dissipation were recorded and tabulated in Table (4.2) the energy at inlet and outlet for rectangular end sill of height 4 cm was found to be 68.397 cm and 26.681 cm for a discharge of 1.65 lit/sec resulting in the total energy loss of 41.716 cm, while the total energy loss was found to be 42.195 cm, 42.147 cm, 41.577 cm and 41.917 cm for triangular, semi-circular, diagonal vertical upstream and diagonal vertical downstream end sill respectively. The total energy loss was found to be 43.316 cm, 43.600 cm and 43.590 cm for rectangular, triangular and semi-circular end sill at a discharge of 4.4 lit/sec, and the total energy loss was observed as 44.871 cm and 42.942 cm for diagonal vertical upstream and diagonal vertical downstream end sill respectively. The total energy loss was found to be 43.098 cm, 43.336 cm, 42.919 cm, 43.242 cm and 41.058 cm for rectangular, triangular, semi-circular, diagonal vertical

Table 4.1 Observed hydraulic jump parameters and energy dissipation for different discharges using selected shapes and end sill height 3 cm

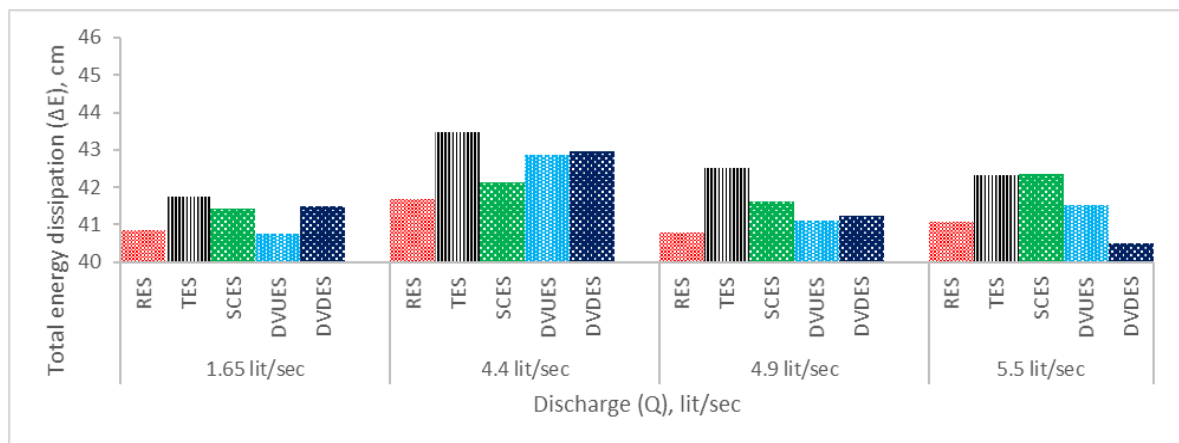
Discharge (Q), lit/sec	Shape of end sill	Flow energy at inlet (E_i), cm	Flow energy at outlet (E_o), cm	Total energy loss (ΔE), cm	Hydraulic jump efficiency (JE), %	Relative loss of energy (RL), %	Height of jump, (hj), cm
1.65	RES	68.973	25.530	43.443	37.014	62.985	4.336
	TES	68.390	25.327	43.063	37.033	62.966	3.900
	SCES	69.082	25.678	43.404	37.170	62.829	4.533
	DVUES	68.351	25.370	42.981	37.117	62.882	3.933
	DVDES	68.904	24.986	43.928	36.262	63.757	3.683
4.4	RES	73.468	28.752	44.716	39.135	60.864	4.464
	TES	74.325	28.398	45.927	38.207	61.792	4.194
	SCES	72.909	29.242	43.667	40.107	59.892	4.900
	DVUES	73.861	28.551	45.310	38.655	61.344	4.300
	DVDES	73.739	28.308	45.431	38.389	61.610	3.840
4.9	RES	73.990	29.645	44.345	40.066	59.993	4.934
	TES	73.338	29.056	45.282	39.619	61.744	3.636
	SCES	73.720	30.173	43.547	40.929	59.070	5.533
	DVUES	73.720	29.554	44.166	40.089	59.910	4.666
	DVDES	73.295	29.749	43.546	40.588	59.411	4.690
5.5	RES	74.564	30.360	44.203	40.716	59.281	4.973
	TES	74.073	30.041	44.032	40.555	59.444	4.167
	SCES	74.550	31.021	43.432	41.609	58.258	5.900
	DVUES	74.027	30.240	43.787	40.850	59.150	4.450
	DVDES	74.242	30.576	43.666	41.184	58.815	5.100



(a) End sill height of 3 cm



(b) End sill height of 4 cm



(c) End sill height of 5 cm

Fig. 4.1 Total energy dissipation for different shapes of end sill at selected discharges and heights of end sill

upstream and diagonal vertical downstream end sill respectively for a discharge of 4.9 lit/sec for 4 cm height of end sill. In case of 5.5 lit/sec discharge, the total energy loss was found to be 44.084 cm, 43.502 cm for rectangular and triangular end sill, while there was a very little difference in amount of total energy loss for the semi-circular, diagonal vertical upstream and diagonal vertical downstream end sill height of 4 cm respectively.

The recorded observations were recorded and compared in Table (4.2), with all selected shapes of end sill which indicate that there was a little variation in the amount of total energy loss for all selected discharges. The graphical representation of hydraulic energy dissipation behaviour for all shape of end sill at 4 cm height is shown in Fig. 4.1 (b)

4.1.3 Hydraulic energy dissipation behaviour using different shapes for a 5 cm height of end sill at selected discharges

The observation of total energy loss for selected discharge for 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec were recorded and tabulated in Table (4.3), the total energy loss of rectangular end sill with height of 5 cm was found to be 40.848 cm at a discharge of 1.65 lit/sec while the total energy loss for triangular, semi-circular, diagonal vertical upstream and diagonal vertical downstream end was observed as 41.763 cm, 41.427 cm, 40.758 cm and 41.482 cm respectively. Similarly for the discharge of 4.4 lit/sec, the total energy loss was found to be 41.684 cm, 43.488 cm and 42.139 cm for rectangular, triangular and semi-circular end sill height of 5 cm respectively. The total energy loss was observed as 41.684 cm, 43.488 cm, 42.139 cm, 42.883 cm and 42.965 cm for the shape of rectangular, triangular, semi-circular diagonal vertical upstream and diagonal vertical downstream end sill at a discharge of 4.4 lit/sec and height of end sill as 5 cm respectively. The total energy loss was found to be 40.796 cm and 42.507 cm, while for the shape of semi-circular, diagonal vertical upstream and diagonal vertical downstream end sill the total energy loss was observed as 41.637 cm, 41.120 cm and 41.238 cm at a discharge of 4.9 lit/sec and end sill height of 5 cm respectively. In this case, the minimum energy loss was observed as 40.796 cm for rectangular end sill. The total energy loss was found to be 41.095 cm, 41.500 cm, 43.293 cm, 44.250 cm and 40.515 cm for rectangular, triangular, semi-circular, diagonal vertical upstream and diagonal vertical downstream end sill at a discharge of 5.5 lit/sec respectively. In this case the maximum energy loss was observed as 42.367 cm for semi-circular end sill at a discharge of 5.5 lit/sec and end sill height 5 cm.

The observation recorded in Table (4.3) clearly indicate that for all selected shapes of end sill with height of 5 cm, the total energy loss has an increasing trend with increase in increased. The graphical representation of total energy loss for this case is are shown in Fig. 4.1(c)

4.2 Hydraulic Energy Dissipation Behaviour Using Different Heights of End Sill for a particular Shape at Selected Discharges

The hydraulic energy dissipation behaviour using different heights of 3cm, 4 cm and 5 cm for a particular shape of end sill at selected discharges of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec were recorded and analysed to see the effect of end sill shape on hydraulic energy dissipation. The recorded observations are tabulated in Table (4.4 to 4.8).

4.2.1 Hydraulic energy dissipation behaviour using different heights for rectangular shape of end sill at selected discharges

The recorded values of hydraulic jump parameters tabulated in Table (4.4) indicate that for the rectangular end sill (RES) for all different heights of 3 cm, 4 cm and 5 cm in the selected range of discharge, the flow energy dissipated ranged from 41.713 cm to 45.927 cm, the relative loss of energy ranged from 57.917 cm to 62.966 cm while the hydraulic jump efficiency ranged from a minimum 37.033% to a maximum of 42.080%. The flow energy at inlet and outlet was found to be 68.390 cm and 25.327 cm resulting in the total energy dissipation of 43.063 cm at a discharge of 1.65 lit/sec for 3 cm height of end sill. Similarly, the total energy dissipation of 45.927cm, 44.282 cm and 44.032 cm was observed at discharges of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively. In case of 4 cm height of end sill the flow energy at inlet and outlet was found to be 68.478 cm and 26.383 cm respectively resulting in the total energy dissipation of 42.195 cm. It was observed that the total energy dissipation of 43.600 cm, 43.336 cm and 43.503 cm occurred at discharges of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively. Similarly in case of a 5 cm height of end sill, the total energy dissipation was found to be 41.763 cm, 43.488 cm, 42.507 cm and 42.320 cm at the corresponding discharges of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively.

The observation recorded in Table (4.4) clearly indicate that for all selected heights of end sill the minimum energy dissipation occurs at a discharge of 1.65 lit/sec while there

Table 4.4 Observed hydraulic jump parameters and energy dissipation for different discharges using selected heights of rectangular end sill

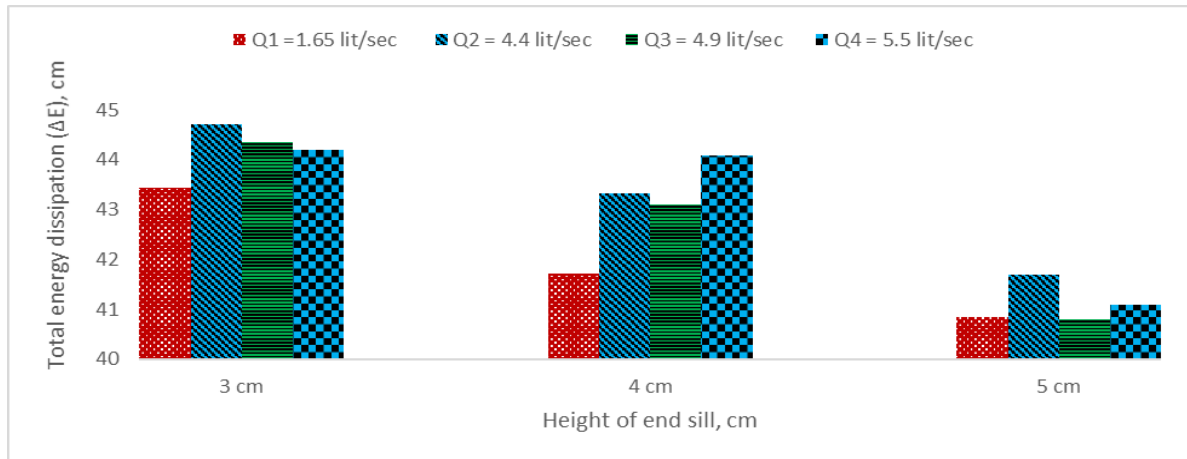
End sill Height, cm	Discharge (Q), lit/sec	Depth of flow at inlet (d _i),cm	Depth of flow at outlet (d _o), cm	Flow velocity at inlet (V _i), cm	Flow velocity at outlet (V _o), cm	Froude number before jump (Fr ₂)	Froude number after jump (Fr ₂)	Flow energy at inlet (E _i), cm	Flow energy at outlet (E _o), cm	Total energy dissipation (ΔE),cm	Hydraulic jump efficiency (JE),%	Relative loss of energy (RL), %	Height of jump (h _j), cm
3.00	1.65	1.830	6.166	90.163	26.759	2.127	0.344	68.973	25.530	43.443	37.014	62.985	4.336
	4.40	3.866	8.330	113.812	52.821	1.848	0.584	73.468	28.752	44.716	39.135	60.864	4.464
	4.90	4.266	9.200	114.861	53.260	1.775	0.560	73.990	29.645	44.345	40.066	59.993	4.934
	5.50	4.760	9.733	115.546	56.508	1.690	0.578	74.564	30.360	44.203	40.716	59.281	4.973
4.00	1.65	2.030	7.430	81.280	22.207	1.821	0.258	68.397	26.681	41.716	39.009	60.990	5.400
	4.40	3.716	10.680	118.406	41.198	1.961	0.402	73.861	30.545	43.316	41.354	58.645	6.964
	4.90	4.200	11.033	116.666	44.410	1.817	0.426	74.136	31.038	43.098	41.866	58.133	6.833
	5.50	4.480	11.160	122.767	49.283	1.851	0.471	75.481	31.397	44.084	41.595	58.404	6.680
5.00	1.65	1.966	8.516	83.926	19.375	1.911	0.211	68.555	27.707	40.848	40.415	59.584	6.550
	4.40	4.166	11.410	105.616	38.562	1.652	0.364	72.851	31.167	41.684	42.781	57.218	7.244
	4.90	4.683	12.710	104.633	38.552	1.543	0.345	73.263	32.467	40.796	44.315	55.684	8.027
	5.50	5.083	13.050	108.203	42.145	1.532	0.372	74.050	32.955	41.095	44.503	55.496	7.967

Table 4.5 Observed hydraulic jump parameters and energy dissipation for different discharges using selected heights of triangular end sill

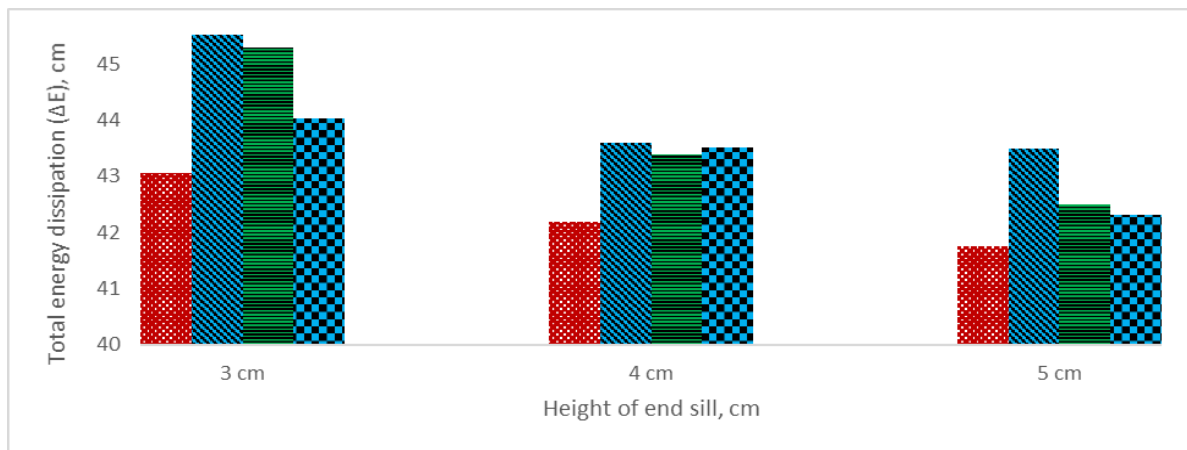
End sill Height, cm	Discharge (Q), lit/sec	Depth of flow at inlet (d _i),cm	Depth of flow at outlet (d _o), cm	Flow velocity at inlet (V _i), cm	Flow velocity at outlet (V _o), cm	Froude number before jump (Fr ₁)	Froude number after jump (Fr ₂)	Flow energy at inlet (E _i), cm	Flow energy at outlet (E _o), cm	Total energy dissipation (ΔE),cm	Hydraulic jump efficiency (JE),%	Relative loss of energy (RL), %	Height of jump (h _j), cm
3.00	1.65	2.033	5.933	81.160	27.810	1.817	0.346	68.390	25.327	43.063	37.033	62.966	3.900
	4.40	3.566	7.760	123.387	56.701	2.0863	0.649	74.325	28.398	45.927	38.207	61.792	4.194
	4.90	4.630	8.266	105.831	59.278	1.578	0.658	73.338	29.056	45.282	39.619	60.380	3.636
	5.50	5.066	9.233	108.566	59.568	1.540	0.626	74.073	30.041	44.032	40.555	59.444	4.167
4.00	1.65	2.0166	7.000	81.820	23.571	1.827	0.284	68.478	26.383	42.195	38.381	61.518	4.983
	4.40	4.000	9.466	110.000	46.482	1.756	0.482	73.167	29.567	43.600	40.410	59.589	5.466
	4.90	4.250	10.600	115.294	46.226	1.785	0.453	74.025	30.689	43.396	41.457	58.542	6.350
	5.50	4.633	11.050	118.713	49.773	1.761	0.478	74.815	31.318	43.502	41.852	58.147	6.417
5.00	1.65	2.050	7.330	80.487	22.510	1.794	0.265	68.351	26.588	41.763	38.899	61.100	5.280
	4.40	3.733	10.410	117.864	42.242	1.947	0.417	73.813	30.325	43.488	41.083	58.916	6.683
	4.90	4.330	11.08	113.163	44.211	1.736	0.424	73.856	31.079	42.507	42.080	57.919	6.753
	5.50	5.230	12.350	105.162	44.534	1.468	0.404	73.866	32.360	42.320	41.50	56.190	7.120

Table 4.6 Observed hydraulic jump parameters and energy dissipation for different discharges using selected heights of semicircular end sill

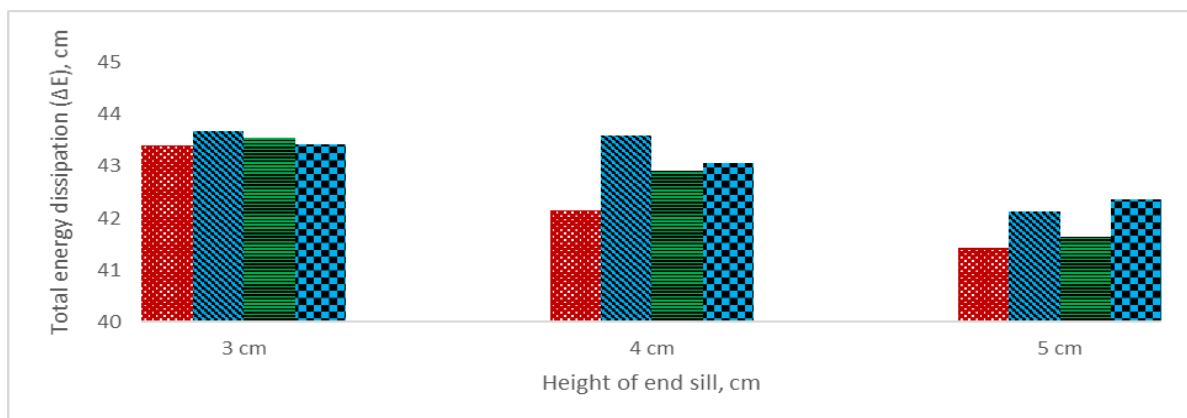
End sill Height, cm	Discharge (Q), lit/sec	Depth of flow at inlet (d _i), cm	Depth of flow at outlet (d _o), cm	Flow velocity at inlet (V _i), cm	Flow velocity at outlet (V _o), cm	Froude number before jump (Fr ₁)	Froude number after jump (Fr ₂)	Flow energy at inlet (E _i), cm	Flow energy at outlet (E _o), cm	Total energy dissipation (ΔE), cm	Hydraulic jump efficiency (JE), %	Relative loss of energy (RL), %	Height of jump (h _j), cm
3.00	1.65	1.800	6.333	91.666	26.054	2.181	0.330	69.082	25.678	43.404	37.170	62.829	4.533
	4.40	4.133	9.033	106.460	48.710	1.672	0.517	72.909	29.242	43.667	40.107	59.974	4.900
	4.90	4.400	9.933	111.363	49.330	1.695	0.499	73.720	30.173	43.547	40.929	59.070	5.533
	5.50	4.766	10.666	115.400	51.565	1.687	0.504	74.55	31.021	43.432	41.609	58.390	5.900
4.00	1.65	1.733	7.000	95.210	23.571	2.309	0.284	68.430	26.283	42.147	38.408	61.591	5.267
	4.40	3.766	10.280	116.834	42.801	1.922	0.426	73.723	30.213	43.590	40.981	59.018	6.514
	4.90	4.433	10.666	110.534	45.940	1.676	0.449	73.660	30.741	42.919	41.773	58.266	6.233
	5.50	4.733	11.366	116.205	48.389	1.706	0.458	74.615	31.559	43.056	42.295	57.704	6.627
5.00	1.65	2.00	7.816	82.500	21.110	1.862	0.240	68.469	27.042	41.427	39.495	60.504	5.816
	4.40	4.016	11.210	109.561	39.250	1.745	0.374	73.934	30.995	42.139	42.381	57.618	7.194
	4.90	4.583	11.910	106.916	41.141	1.594	0.380	73.409	31.772	41.637	43.280	56.719	7.327
	5.50	4.683	12.333	117.446	44.595	1.733	0.405	74.713	32.346	42.367	43.293	56.706	7.650



(a) Rectangular end sill



(b) Triangular end sill



(c) Semicircular end sill

Fig. 4.2 Total energy dissipation for rectangular, triangular and semicircular end sills at selected discharges and heights of end sill

was no definite trend for maximum energy dissipation at these heights of end sill. The graphical representation of hydraulic energy dissipation behaviour for all selected heights of rectangular end sill (RES) for all selected discharges are shown in Fig. (4.2). In general it was found that as the discharge is increasing the amount of energy dissipation has a decreasing trend for all selected end sill heights.

4.2.2 Hydraulic energy dissipation behaviour using different heights for a triangular shape of end sill at selected discharges

The observed values of hydraulic jump parameter are recorded in Table (4.5), for the triangular shape of end sill (TES) of different heights (3cm, 4cm and 5cm) at all selected discharges of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec. It was found that for a 3cm high end sill, the flow energy at inlet and outlet was 68.390 cm and 25.327 cm resulting in total energy dissipation of 43.063 cm. Similarly the total energy dissipation of 45.927, 45.282 and 44.032 cm observed for the discharges of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec using a height of 3 cm for triangular end sill. In case of 4 cm height of end sill the flow energy at inlet and outlet was found to be 68.478 cm and 26.383 cm at a discharge of 1.65 lit/sec resulting in the total energy dissipation of 42.195 cm. The total energy loss of 43.600 cm, 43.396 cm and 43.502 cm was observed at the discharge of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively. In case of 5 cm height of end sill the total energy dissipation was found to be 41.763 cm, 43.488 cm, 42.507 cm and 42.320 cm at a discharge of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively.

The observations recorded in Table (4.5), clearly indicate that for all selected heights of triangular end sill the maximum amount of total energy dissipation was found to be 45.282 cm at a discharge of 4.4 lit/sec and end sill height 4 cm for semi-circular. The graphical representation of hydraulic energy dissipation behaviour for all selected heights of triangular shape of end sill as for all selected discharge shown in Fig. 4.2 (b). It was further observed that the trend of energy dissipation with discharge was found on the similar pattern as in case of rectangular end sill.

4.2.3 Hydraulic energy dissipation behaviour using different heights for a semi-circular shape of end sill at selected discharges

The observations recorded in Table (4.6), clearly indicate that for all selected heights of end sill, the minimum energy dissipation was found to be 41.427 cm at a discharge of 1.65 lit/sec for 5 cm height of end sill and the maximum amount of energy

dissipation was observed to be 43.594 cm at a discharge of 4.90 lit/sec for 4 cm height of end sill. The recorded values of hydraulic jump parameters further indicate that for the semi-circular end sill (SCES) for all different heights of the selected discharge range the flow energy at inlet and outlet was found to be 69.082cm and 25.678 cm resulting in the total energy dissipation of 43.404 cm at a discharge of 1.65 lit/sec for 3 cm height of end sill. While the total energy dissipation of 43.667 cm, 43.547 cm and 43.432 cm was observed at a discharge of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively. In case of 4 cm height of end sill the flow energy at inlet outlet was found to be 68.430 cm and 26.283 cm resulting in the total energy dissipation of 42.147 cm while the total energy dissipation of 43.590 cm, 42.919 cm and 43.056 cm was recorded at a discharge of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively. Similarly, with 5 cm height of end sill the total energy dissipation was found to be 41.427 cm, 43.139 cm, 41.637 cm and 42.367 cm at a discharge of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively.

The observations related to energy dissipation recorded for various combinations of discharge and height of end sill for semicircular shaping end sill were plotted and are shown in Fig. 4.2 (c). The graphical representation of hydraulic energy dissipation for semi-circular end sill (SCES) for all selected discharge indicates that similar to earlier cases there was a decreasing trend with the increasing discharge.

4.2.4 Hydraulic energy dissipation behaviour using different heights for a diagonal vertical upstream shape of end sill at selected discharges

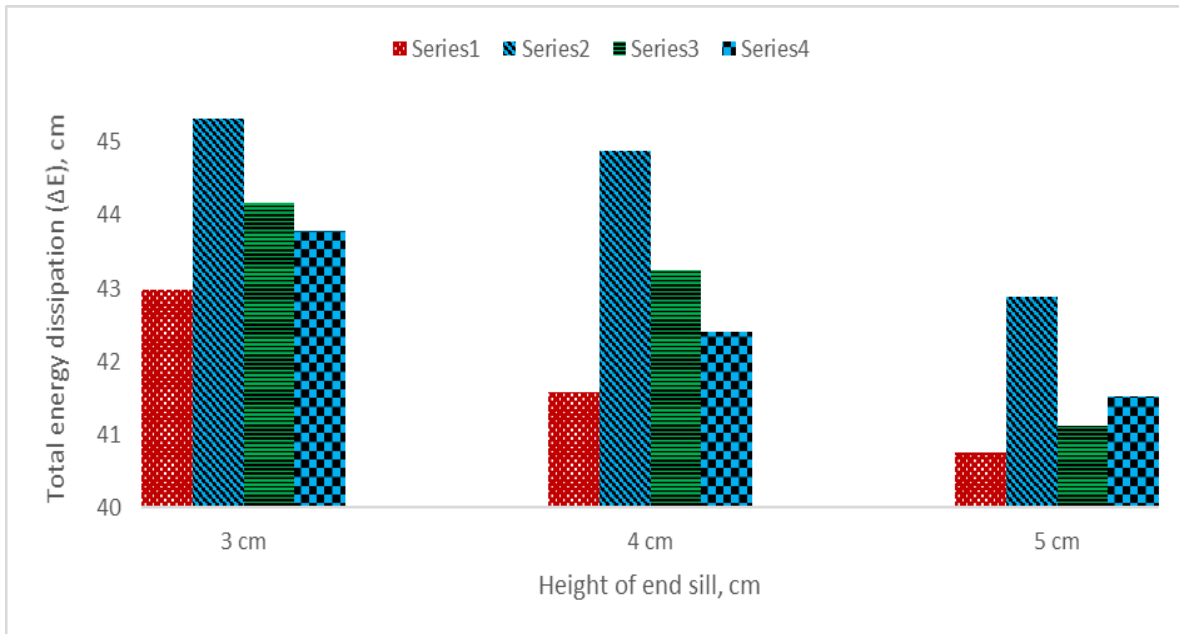
The hydraulic energy dissipation behaviour using different heights for a diagonal vertical upstream shape of end sill at selected discharges was observed by recording hydraulic jump parameters for varying discharge. The observed values of hydraulic jump parameters for this case are recorded in Table (4.7) which clearly indicate that for the diagonal vertical downstream end sill (DVUES) of selected heights of 3 cm, 4 cm and 5 cm for discharges of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec were found to be ranging from a maximum of 62.882 cm for 3cm height at 1.65 lit/sec discharge and a minimum of 55.749 cm for 5cm height and 5.50 lit/sec discharge. The flow energy at inlet and outlet was found to be 62.882 cm and 25.370 cm resulting that total energy dissipation of 37.512 cm for 3cm height at 1.65 lit/sec discharge. Similarly, the total energy dissipation of 45.310 cm, 44.166 cm and 43.787 cm was observed at a discharge of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively for a height of 3 cm diagonal vertical

Table 4.7 Observed hydraulic jump parameters and energy dissipation for different discharges using selected heights of diagonal vertical upstream end sill

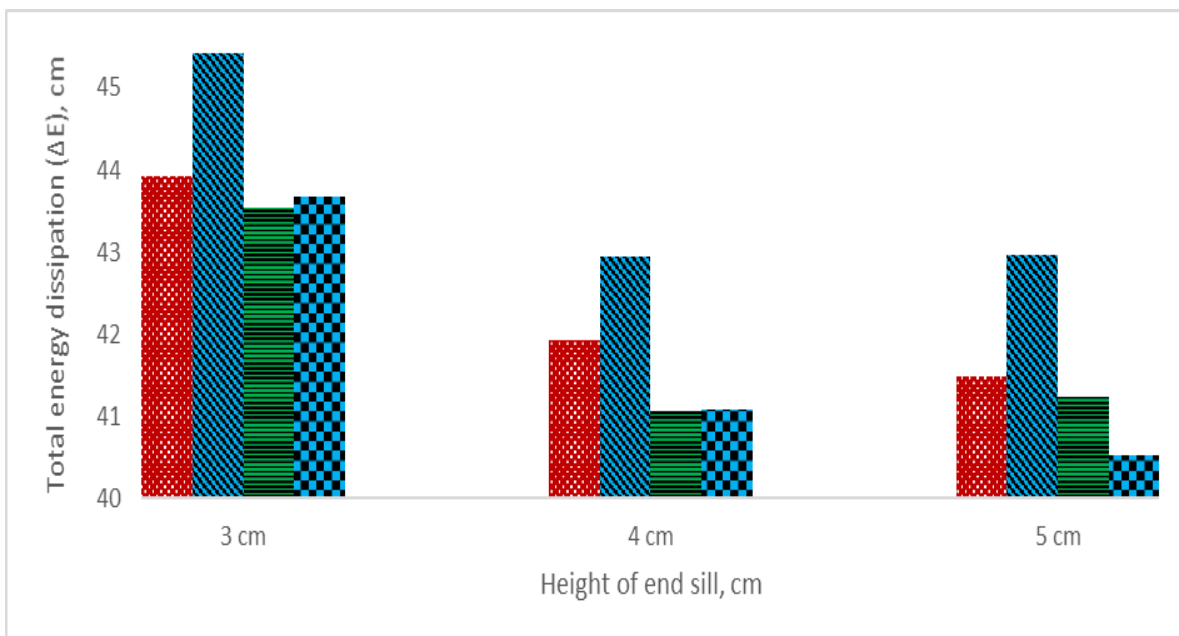
End sill Height, cm	Discharge (Q), lit/sec	Depth of flow at inlet (d _i), cm	Depth of flow at outlet (d _o), cm	Flow velocity at inlet (V _i), cm	Flow velocity at outlet (V _o), cm	Froude number before jump (Fr ₂)	Froude number after jump (Fr ₂)	Flow energy at inlet (E _i), cm	Flow energy at outlet (E _o), cm	Total energy dissipation (ΔE), cm	Hydraulic jump efficiency (JE), %	Relative loss of energy (RL), %	Height of jump (h _j), cm
3.00	1.65	2.050	5.983	80.487	27.578	1.794	0.359	68.351	25.370	42.981	37.117	62.882	3.933
	4.40	3.716	8.016	118.406	54.890	1.961	0.619	73.861	28.551	45.310	38.655	61.344	4.300
	4.90	4.400	9.066	111.363	54.048	1.697	0.573	73.720	29.554	44.166	40.089	59.910	4.666
	5.50	5.100	9.550	107.843	57.591	1.524	0.595	74.027	30.240	43.787	40.850	59.150	4.450
4.00	1.65	1.983	7.700	83.207	21.428	1.886	0.246	68.511	26.934	41.577	39.323	60.696	5.717
	4.40	3.616	9.100	121.68	48.351	2.045	0.511	74.162	29.291	44.871	39.490	60.504	5.484
	4.90	4.200	10.850	116.666	45.161	1.817	0.437	74.137	30.889	43.248	41.664	58.335	6.650
	5.50	4.900	11.816	112.244	46.547	1.618	0.432	74.321	31.920	42.401	42.943	57.051	6.916
5.00	1.65	2.080	8.330	79.326	19.807	1.758	0.219	68.287	27.529	40.758	40.313	59.686	6.250
	4.40	3.650	11.416	120.542	38.542	2.015	0.364	74.056	31.173	42.883	42.093	57.906	7.766
	4.90	4.500	12.660	108.888	38.704	1.639	0.347	73.543	32.423	41.120	44.083	55.912	8.160
	5.50	4.810	13.050	114.345	42.145	1.666	0.372	74.474	32.955	41.519	44.250	55.749	8.240

Table 4.8 Observed hydraulic jump parameters and energy dissipation for different discharges using selected heights of diagonal vertical downstream end sill

End sill Height, cm	Discharge (Q), lit/sec	Depth of flow at inlet (d _i),cm	Depth of flow at outlet (d _o), cm	Flow velocity at inlet (V _i), cm	Flow velocity at outlet (V _o), cm	Froude number before jump (Fr ₂)	Froude number after jump (Fr ₂)	Flow energy at inlet (E _i), cm	Flow energy at outlet (E _o), cm	Total energy dissipation (ΔE),cm	Hydraulic jump efficiency (JE),%	Relative loss of energy (RL), %	Height of jump (h _j), cm
3.00	1.65	1.850	5.333	89.189	29.831	2.093	0.412	68.904	24.986	43.928	36.262	63.757	3.483
	4.40	3.760	7.600	117.021	57.894	1.926	0.670	73.739	28.308	45.431	38.389	61.610	3.840
	4.90	4.660	9.350	105.150	52.406	1.555	0.547	73.295	29.749	43.546	40.588	59.411	4.690
	5.50	4.950	10.050	111.111	54.726	1.594	0.551	74.242	30.576	43.666	41.184	58.815	5.100
4.00	1.65	1.866	7.700	88.424	21.428	2.066	0.246	68.851	26.934	41.917	39.119	60.880	5.834
	4.40	3.733	11.066	117.867	39.761	1.947	0.382	73.813	30.871	42.942	41.920	58.176	7.330
	4.90	4.700	12.383	104.255	39.570	1.535	0.359	73.239	32.181	41.058	43.939	56.060	7.683
	5.50	5.060	13.116	108.695	41.933	1.221	0.369	74.081	33.012	41.069	44.562	55.473	8.056
5.00	1.65	1.850	8.216	89.189	20.082	2.093	0.223	68.903	27.421	41.482	39.796	60.203	6.366
	4.40	3.766	10.933	116.834	40.245	1.924	0.388	73.723	30.758	42.965	41.721	58.278	7.167
	4.90	4.750	12.100	103.157	40.495	1.511	0.371	73.173	31.935	41.238	43.643	56.356	7.350
	5.50	5.116	13.666	107.505	40.265	1.517	0.347	74.006	33.491	40.515	45.254	54.748	8.550



(d) Diagonal vertical upstream end sill



(e) Diagonal vertical downstream end sill

Fig. 4.3 Total energy dissipation for diagonal vertical upstream and diagonal vertical downstream end sill at selected discharges and heights of end sill

upstream end sill. In case of 4 cm height of end sill the flow energy at inlet and outlet was found to be 68.511 cm and 26.934 cm at a discharge of 1.65 lit/sec resulting in the total energy dissipation of 41.577 cm. The total energy loss of 44.871 cm, 43.248 cm and 42.401 cm was observed at discharge of 4.4 lit/sec., 4.9 lit/sec. and 5.5 lit/sec. In case of 5 cm height of end sill the total energy dissipation was found to be 40.758 cm, 42.883 cm, 41.120 cm and 41.519 cm at a discharge of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively.

The observation recorded in Table (4.7) and the graphical representation of hydraulic energy dissipation as shown in Fig. 4.3 (a) clearly indicate that for all selected heights of diagonal vertical upstream end sill the maximum amount of total energy dissipation was found to be 45.310 cm with height of end sill 3 cm at a discharge of 4.4 lit/sec. Interestingly, the amount of energy dissipation for different heights of end sill initially increased as the discharge was increased from 1.65 lit/sec to 4.4 lit /sec after that the further increase in discharge resulted in the decrease in amount of energy dissipated.

4.2.5 Hydraulic energy dissipation behaviour using different heights for a diagonal vertical downstream shape of end sill at selected discharges

The observation recorded in Table (4.8) and the graphical representation of hydraulic energy dissipation as shown in Fig. 4.3 (b) clearly indicate that for all selected heights of diagonal vertical upstream end sill the maximum amount of total energy dissipation was found to be 45.431 cm with height of end sill 3 cm at a discharge of 4.4 lit/sec. Similar to earlier case in this case also the amount of energy dissipation for different heights of end sill initially increased as the discharge was increased from 1.65 lit/sec to 4.4 lit /sec after that the further increase in discharge resulted in the decrease in amount of energy dissipated diagonal vertical downstream end sill (DVDES) for all different heights.

The flow energy at inlet and outlet was found to be 68.904 cm and 24.986 cm resulting in the total energy dissipation of 43.928 cm at a discharge of 1.65 lit/sec for 3 cm height of end sill. The total amount of energy dissipation of 45.431 cm, 43.546 cm and 43.666 cm was observed at a discharge of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively. In case of 4 cm height of end sill the flow energy at inlet outlet was found to be 68.851 cm and 26.934 cm resulting in the total energy dissipation of 41.917 cm. Similarly, the total energy dissipation of 42.942 cm, 41.058 cm and 41.069 cm was found at a discharge of 4.4

lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively. The total amount of energy dissipation was found to be 41.482 cm, 42.965 cm, 41.238 cm and 40.515 cm was observed with 5 cm height of end sill at a discharge of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively.

4.3 Relative Loss of Energy and Hydraulic Jump Efficiency Using Different Shapes for particular Height of End Sill at Selected Discharges

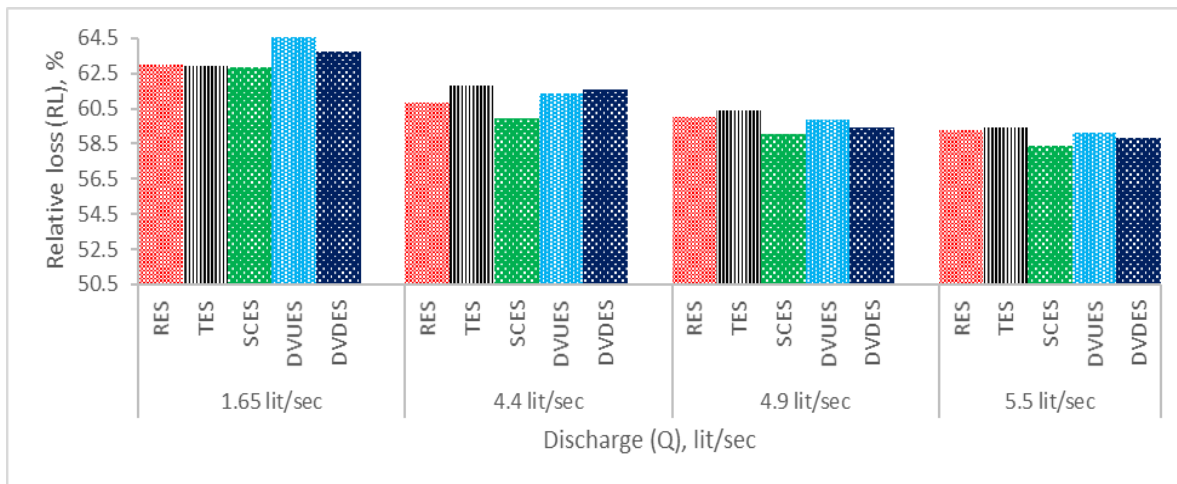
The relative loss of energy and hydraulic jump efficiency using different shapes such as rectangular end sill (RES), triangular end sill (TES), semi-circular end sill (SCES), diagonal vertical upstream end sill (DVUES) and diagonal vertical downstream end sill (DVDES) for a particular height of end sill at selected discharges of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec were recorded and analysed to see the effect of end sill shape on relative loss of energy and hydraulic jump efficiency were recorded and tabulated in Table 4.1 to 4.3.

4.3.1 Relative loss of energy and hydraulic jump efficiency using different shapes for 3 cm height of end sill at selected discharges

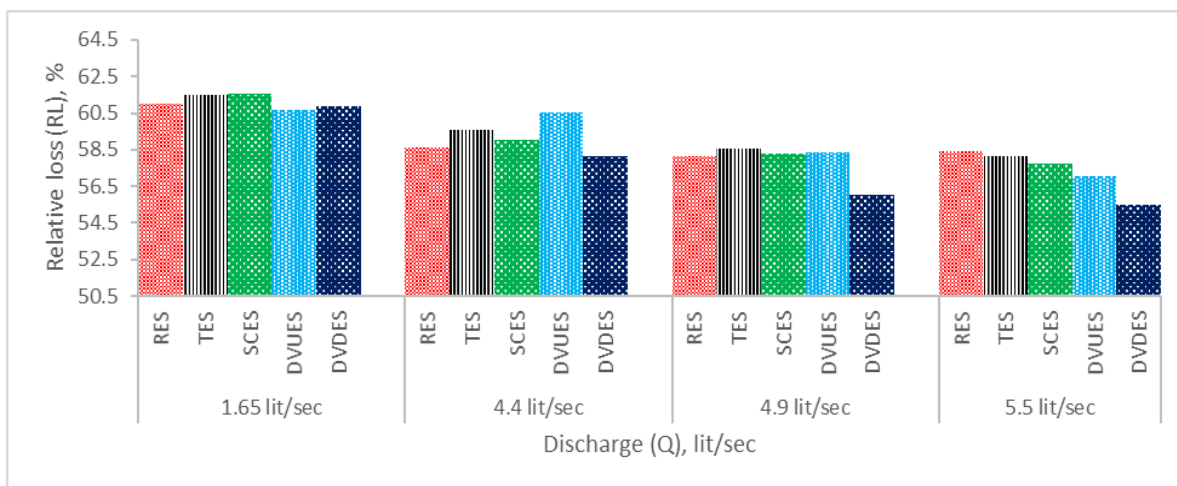
The observed values of relative loss of energy and hydraulic jump efficiency are recorded in Table (4.1). From the recorded data it became evident that for rectangular end sill height of 3 cm the hydraulic jump efficiency and relative loss of energy were found to be 37.014% and 62.985% while the relative loss of energy was found to be 60.864%, 59.993% and 59.281% at selected discharge of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec and the hydraulic jump efficiency at selected discharges was found to be 39.135%, 40.066% and 40.716% respectively. In this case the maximum hydraulic jump efficiency was found to be 40.716% and the minimum relative loss of energy was found to be 59.281% at a discharge of 5.5 lit/sec. In case of triangular end sill for same height of 4 cm, the hydraulic jump efficiency and relative loss of energy were found to be 37.033% and 62.966% while at the selected discharges of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec of the relative loss of energy was found to be 61.792%, 60.380% & 59.44% and hydraulic jump efficiency was found to be 38.207%, 39.619% & 40.555% respectively. Similarly, in case of semi-circular end sill and vertical diagonal upstream end sill the relative loss of energy at selected discharge was found to be 62.829%, 59.974%, 59.070%, and 58.390% while the hydraulic jump efficiency for diagonal vertical upstream end sill at discharge of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec was found to be 37.117%, 38.655%, 40.089% and 40.850%. In case of diagonal vertical

Table 4.3 Observed hydraulic jump parameters and energy dissipation for different discharges using selected shapes and end sill height 5 cm

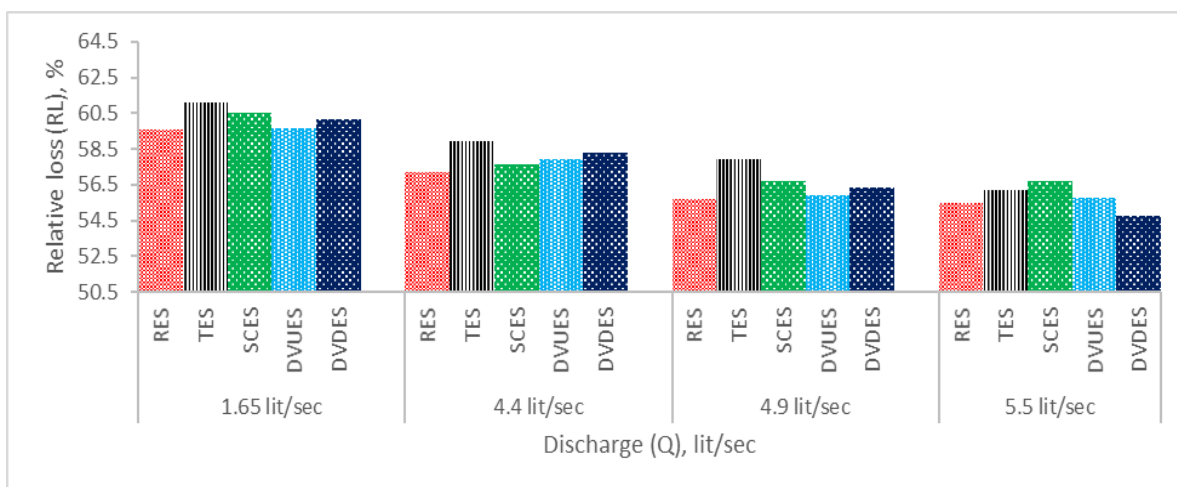
Discharge (Q), lit/sec	Shape of end sill	Flow energy at inlet (E_i), cm	Flow energy at outlet (E_o), cm	Total energy loss (ΔE), cm	Hydraulic jump efficiency (JE), %	Relative loss of energy (RL), %	Height of jump, (hj), cm
1.65	RES	68.555	27.707	40.848	40.415	59.584	6.550
	TES	68.351	26.588	41.763	38.899	61.100	5.280
	SCES	68.469	27.042	41.427	39.495	60.504	5.816
	DVUES	68.287	27.529	40.758	40.313	59.686	6.250
	DVDES	68.903	27.421	41.482	39.796	60.203	6.366
4.4	RES	72.851	31.167	41.684	42.781	57.218	7.244
	TES	73.813	30.325	43.488	41.083	58.916	6.686
	SCES	73.934	30.995	42.139	42.381	57.618	7.194
	DVUES	74.056	31.173	42.883	42.093	57.906	7.766
	DVDES	73.723	30.758	42.965	41.721	58.278	7.167
4.9	RES	73.263	32.467	40.796	44.315	55.684	8.027
	TES	73.856	31.079	42.507	42.080	57.919	6.753
	SCES	73.409	31.772	41.637	43.280	56.719	7.327
	DVUES	73.543	32.423	41.120	44.083	55.912	8.160
	DVDES	73.173	31.935	41.238	43.643	56.356	7.350
5.5	RES	74.050	32.955	41.095	44.503	55.496	7.967
	TES	73.866	32.360	42.320	41.500	56.190	7.120
	SCES	74.713	32.346	42.367	43.293	56.706	7.650
	DVUES	74.474	32.955	41.519	44.250	55.749	8.240
	DVDES	74.006	33.491	40.515	45.250	54.745	8.550



(a) 3 cm height



(b) 4 cm height



(c) 5 cm height

Fig. 4.7 Relative loss of energy for different shapes of end sill at selected discharges and height of end sill

downstream end sill hydraulic jump efficiency was found to be 36.262%, 38.389%, 40.588% and 41.184% at selected discharges while relative loss of energy was recorded as 63.737%, 61.610%, 59.411% and 58.851% respectively.

The values of relative loss of energy and hydraulic jump efficiency were recorded in Table (4.1), which indicate that the hydraulic jump efficiency increased with decrease in relative loss of energy for increasing discharge. The graphical representations of relative loss of energy and hydraulic jump efficiency are shown in Fig 4.1 (a) and 4.7 (b)

4.3.2 Relative loss of energy and hydraulic jump efficiency using different shapes for 4 cm height of end sill at selected discharges

The values of hydraulic jump efficiency and relative loss of energy were recorded in Table 4.2 and analysed. It was observed that for rectangular end sill of height of 4 cm the hydraulic jump efficiency was found to be 39.009% at a discharge of 1.65 lit/sec while relative loss of energy was found to be 60.990%. In case of discharge 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec the hydraulic jump efficiency was found to be 41.354%, 41.866% and 41.395% and resulting in relative loss of 58.645%, 58.133% and 58.404% respectively. Similarly, in case of triangular end sill the hydraulic jump efficiency was found to be 38.381%, 40.410%, 41.457% and 41.852% at respective discharge of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec while the relative loss of energy was found to be 61.618%, 59.589%, 58.542% and 58.147% . The observations reveal that in case of semi-circular end sill, the relative loss of energy and hydraulic jump efficiency were found to be 61.591% and 38.408% at a discharge of 1.65 lit/sec and in case of selected discharge of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec the relative loss was found to be 40.981%, 41.773%, and hydraulic jump efficiency was found to be 42.295% and 59.018%, 58.266%, 57.704% respectively. In case of diagonal vertical upstream end sill and diagonal vertical downstream end sill the hydraulic jump efficiency was found to be 39.323% and 39.119% at a discharge of 1.65 lit/sec resulting in the relative loss of energy as 60.696% and 60.880%. For the same height of diagonal vertical upstream end sill and diagonal vertical downstream end sill relative loss of energy was found to be 60.504%, 58.335% and 57.051% at discharge of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec. The hydraulic jump efficiency at same selected discharge was observed that 39.490%, 41.664% and 42.943% for diagonal vertical upstream end sill. In case of diagonal vertical downstream end sill a little variation was found in the amount of relative loss of energy.

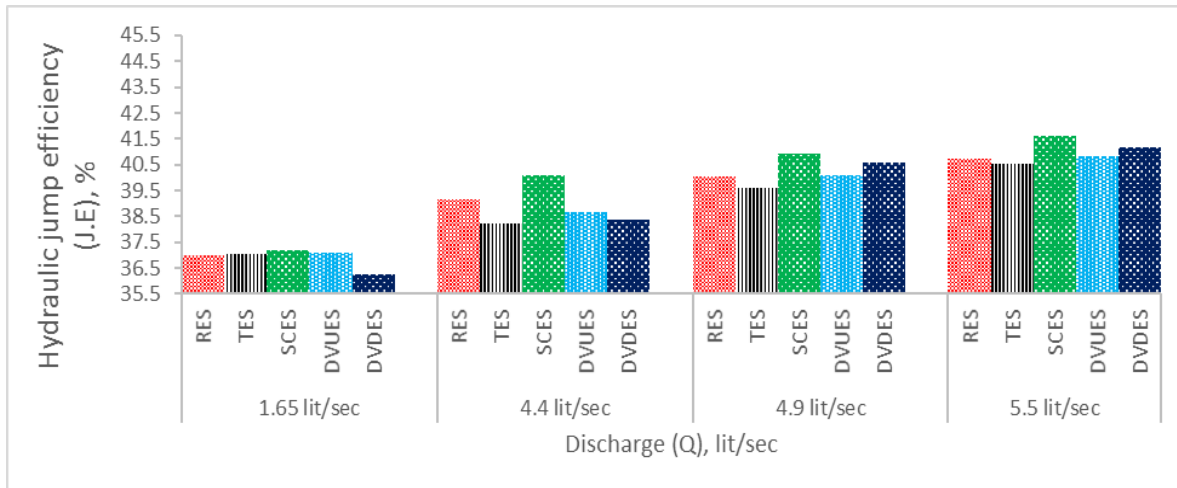
The observations were analysed for the values of relative loss of energy and hydraulic jump efficiency for selected shape of end sill with height of 4 cm and are recorded in Table (4.2). The recorded data indicate that the minimum relative loss of energy was found to be 55.473% at a discharge of 1.65 lit/sec and maximum hydraulic jump efficiency was found to be 44.562% for diagonal vertical downstream end sill at a discharge of 5.5 lit/sec. The graphical representation as shown in Fig. 4.1 (b) and 4.7 (b) for hydraulic jump efficiency reveal an increasing trend while the relative loss of energy has the decreasing trend for all selected discharges and shapes of end sill of height 4 cm

4.3.3 Relative loss of energy and hydraulic jump efficiency using different shapes for 5 cm height of end sill at selected discharges

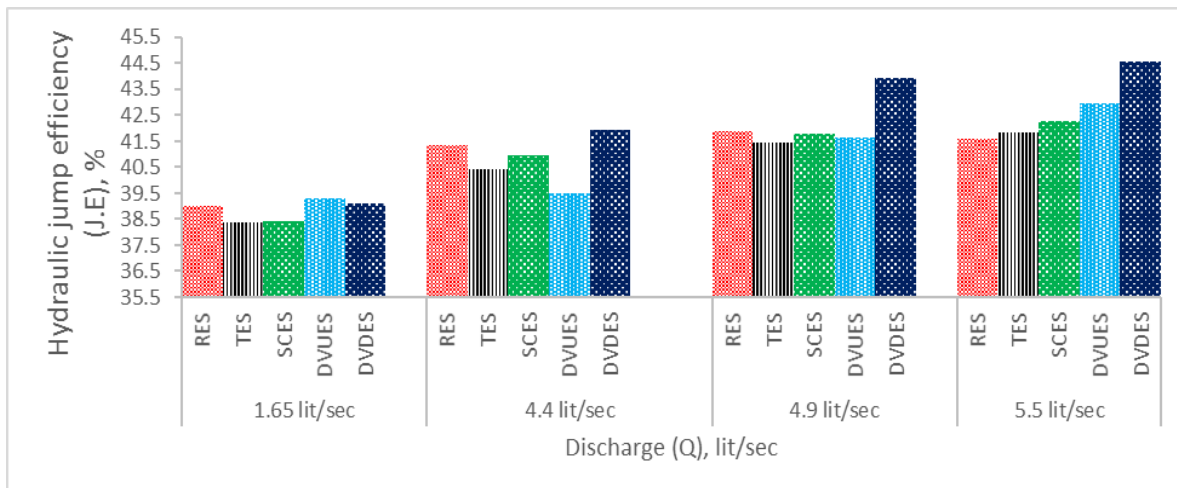
Analysed values of hydraulic jump efficiency and relative loss of energy for different shapes of end sill at 5 cm height were recorded in Table (4.3) for rectangular end sill. The values of hydraulic jump efficiency and relative loss of energy were found to be 40.415% and 59.584% at a discharge of 1.65 lit/sec. Similarly, for the discharge of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec the hydraulic jump efficiency was found to be 42.781%, 44.315% and 44.503% resulting in the relative loss of energy as 57.281%, 55.684% and 55.496% respectively. In case of triangular end sill, the relative loss of energy was found to be 61.100%, 58.916%, 57.919% and 56.190% at discharge of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec while the hydraulic jump efficiency was found to be 38.899%, 41.083%, 42.080% and 41.500% respectively. In case of semi-circular end sill the hydraulic jump efficiency and relative loss of energy were found to be 39.495% and 60.504% at a discharge of 1.65 lit/sec while at the discharge of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec, the hydraulic jump efficiency was found to be 42.381%, 43.280% and 43.293% and the relative loss of energy was found to be 57.618%, 56.719% and 56.706% respectively. In case of diagonal vertical upstream end sill the hydraulic jump efficiency was observed as 40.313%, 42.093%, 44.083% and 44.250% at a discharge of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec while resulting relative loss of energy was found to be 59.686%, 57.906%, 55.912% and 55.749% respectively. The hydraulic jump efficiency in case of diagonal vertical downstream end sill was found to be 39.796%, 41.721%, 43.643% and 45.250% and the relative loss of energy was recorded as 60.203%, 58.278%, 56.356% and 54.748% at a discharge of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively.

Table 4.2 Observed hydraulic jump parameters and energy dissipation for different discharges using selected shapes and end sill height 4 cm

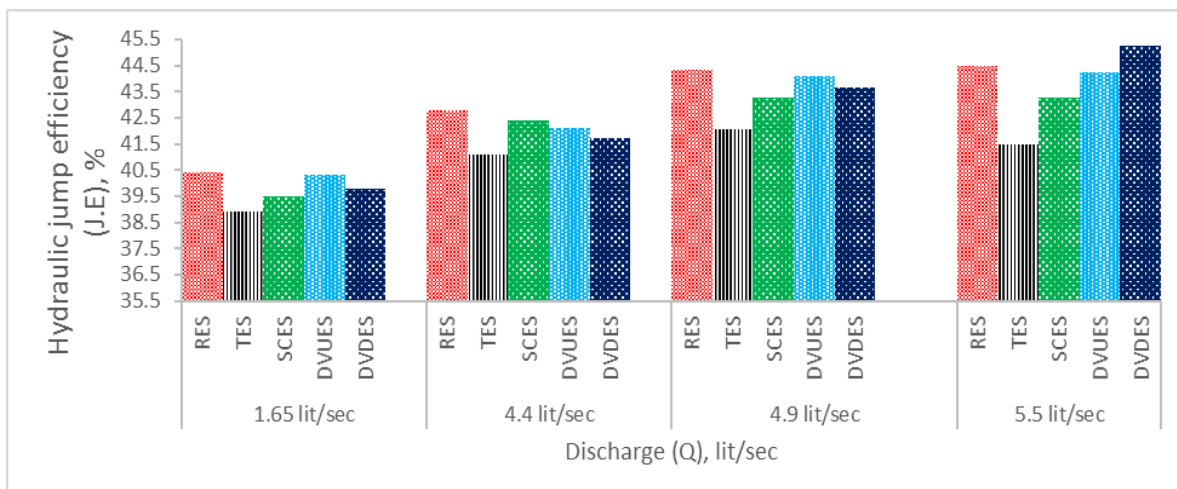
Discharge (Q), lit/sec	Shape of end sill	Flow energy at inlet (E_i), cm	Flow energy at outlet (E_o), cm	Total energy loss (ΔE), cm	Hydraulic jump efficiency (JE), %	Relative loss of energy (RL), %	Height of jump, (hj), cm
1.65	RES	68.397	26.681	41.716	39.009	60.990	5.400
	TES	68.478	26.383	42.195	38.381	61.618	4.983
	SCES	68.430	26.283	42.147	38.408	61.591	5.267
	DVUES	68.511	26.934	41.577	39.323	60.686	5.717
	DVDES	68.851	26.934	41.917	39.119	60.880	5.834
4.4	RES	73.861	30.545	43.316	41.354	58.645	6.964
	TES	73.167	29.567	43.600	40.410	59.589	5.466
	SCES	73.723	30.213	43.590	40.981	59.126	6.514
	DVUES	74.162	29.291	44.871	39.490	60.504	5.484
	DVDES	73.813	30.871	42.942	41.920	58.176	7.330
4.9	RES	74.136	31.038	43.098	41.866	58.133	6.833
	TES	74.025	30.689	43.336	41.457	58.542	6.350
	SCES	73.660	30.741	42.919	41.773	58.266	6.233
	DVUES	74.137	30.889	43.248	41.664	58.335	6.650
	DVDES	73.239	32.181	41.058	43.939	56.060	7.683
5.5	RES	75.481	31.397	44.084	41.595	58.404	6.680
	TES	74.815	31.318	43.502	41.852	58.147	6.417
	SCES	74.615	31.559	43.056	42.295	57.704	6.627
	DVUES	74.321	31.920	42.401	42.943	57.051	6.916
	DVDES	74.081	33.012	41.069	44.562	55.437	8.052



(a) 3 cm height

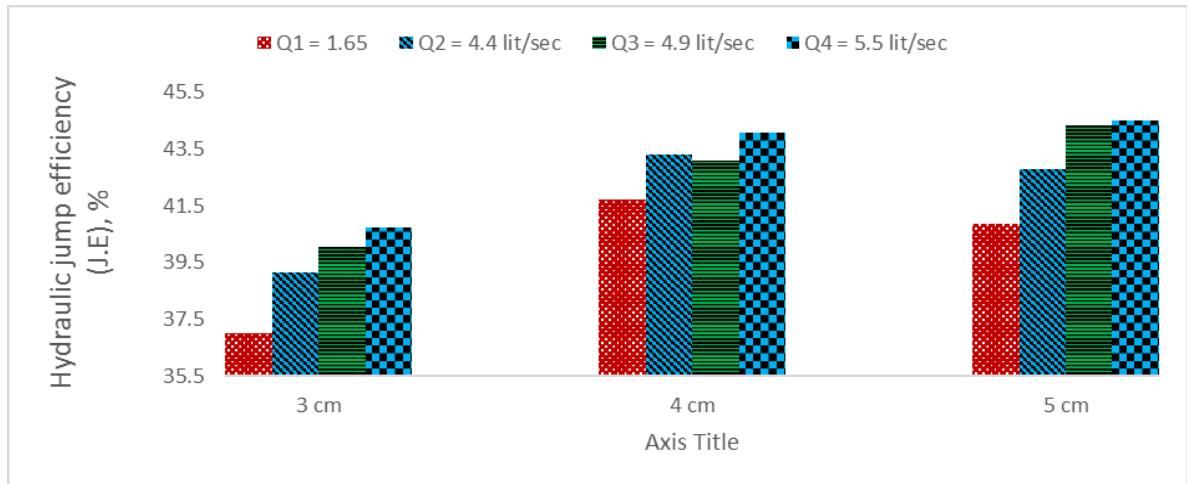


(b) 4 cm height

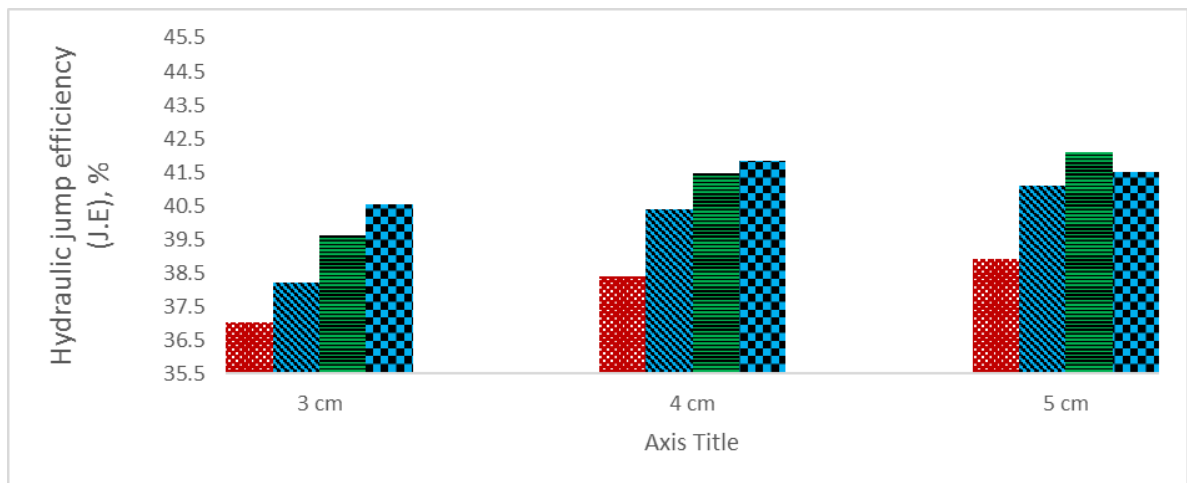


(c) 5 cm height

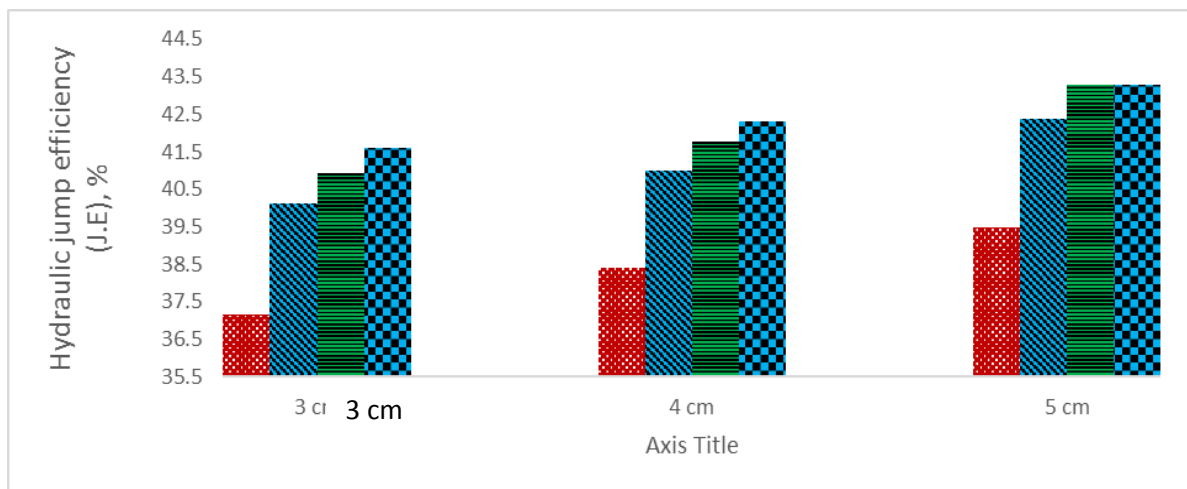
Fig.4.4 Hydraulic jump efficiency for different shapes of end sill at selected discharges and heights of end sill



(a) Rectangular end sill

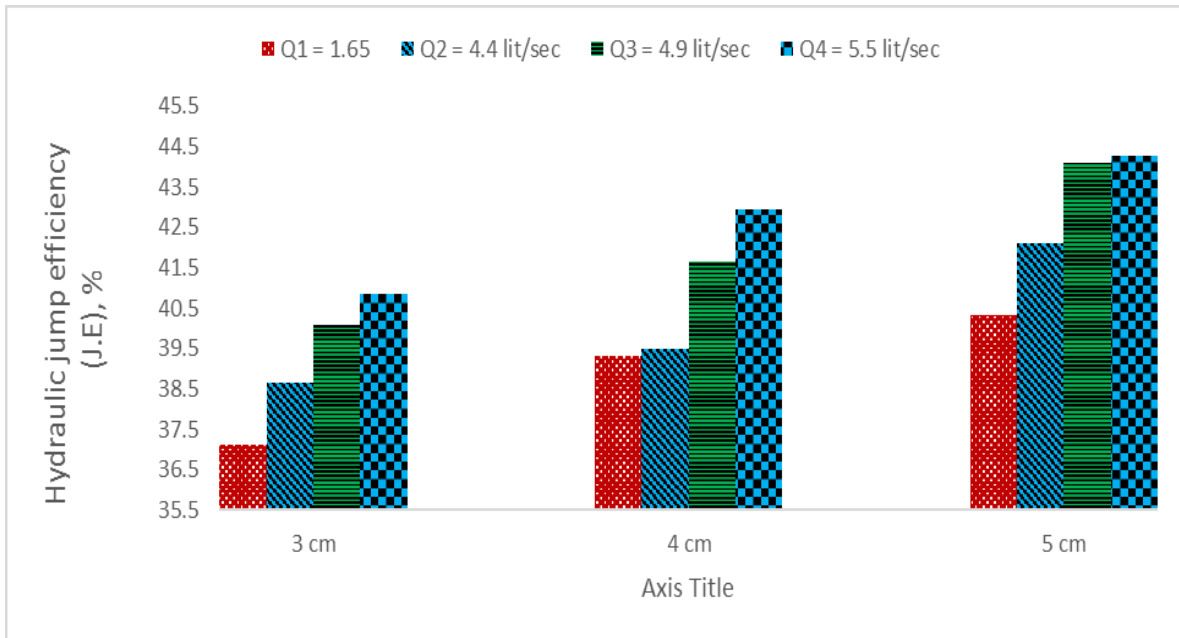


(b) Triangular end sill

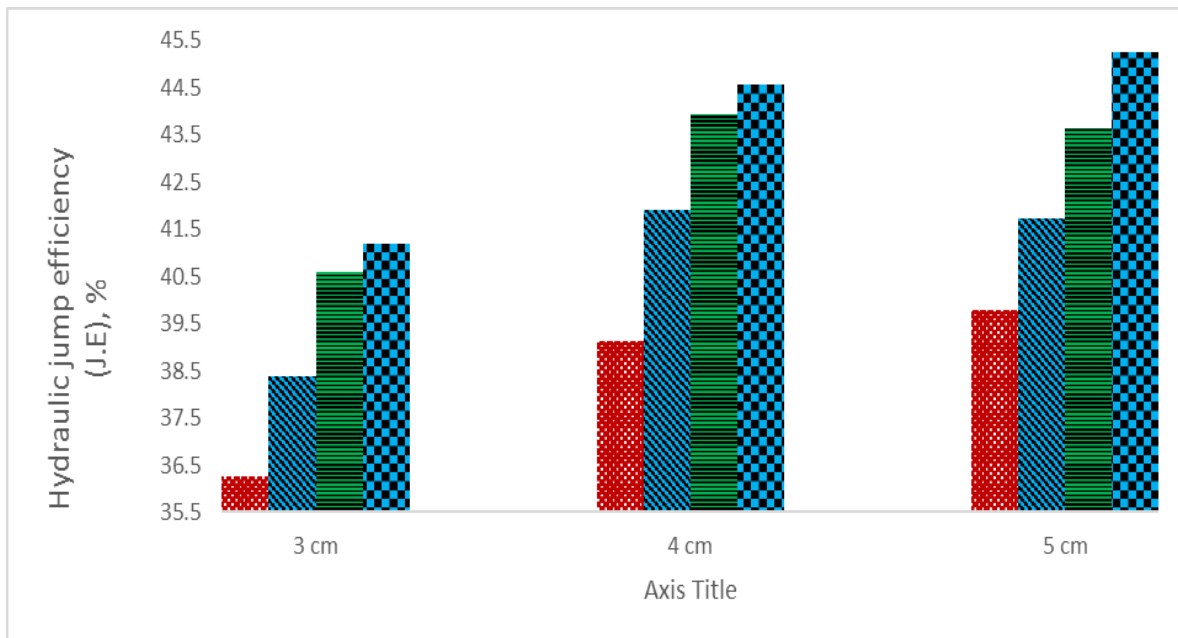


(c) Semicircular end sill

Fig. 4.5 Hydraulic jump efficiency for rectangular, triangular and semi- circular end sills at selected discharges and heights of end sill



(d) Diagonal vertical upstream end sill



(e) Diagonal vertical downstream end sill

Fig. 4.6 Hydraulic jump efficiency for diagonal vertical upstream and diagonal vertical downstream end sills at selected discharges and heights of end sill

The graphical representation shown in Fig.4.7(c) and 4.1(c) and recorded values in Table (4.3) clearly reveal that the maximum relative loss of energy was found to be 61.100% at a discharge of 1.65 lit/sec and maximum hydraulic jump efficiency was found to be 45.250% at a discharge of 5.5 lit/sec shape of diagonal vertical downstream end sill.

4.4 Relative Loss of Energy and Hydraulic Jump Efficiency Using Different Heights for particular Shape of End Sill at Selected Discharges

The relative loss of energy and hydraulic jump efficiency using different heights for a particular shape of end sill at selected discharges of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec were recorded and analysed to see the effect of end sill heights on relative loss of energy and hydraulic jump efficiency. The observations are recorded in Table (4.4) and described in detail in following sections.

4.4.1 Relative loss of energy and hydraulic jump efficiency using different heights for rectangular shape of end sill at selected discharges

The observed values of relative loss of energy and hydraulic jump efficiency for the rectangular end sill (RES) of different heights of 3 cm, 4 cm and 5 cm at selected discharges of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec are tabulated in Table (4.4). The hydraulic jump efficiency and relative loss of energy was recorded as 37.014% and 62.985% at a discharge of 1.65 lit/sec. For the discharges of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec, the hydraulic jump efficiency found to be varying from 37.014% to 40.716% and the relative loss of energy varied from 62.985% to 59.281%. In the case of 4 cm height of end sill, the hydraulic jump efficiency was found to be 39.009% at a discharge of 1.65 lit/sec resulting in the relative loss of energy of 60.990%. Similarly, for the discharges of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec the hydraulic jump efficiency was found to be 41.354%, 41.866% and 41.594% and the values of relative loss of energy were recorded as 60.990%, 58.645% and 58.133% respectively. In case of 5 cm height of end sill the relative loss of energy was found to be 59.584%, 57.218%, 55.684% and the hydraulic jump efficiency was found to be 40.415%, 42.781% 44.315% and 44.503% for the respective discharges of 1.65 lit/sec ,4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively.

The observed values of relative loss of energy and hydraulic jump efficiency for rectangular end sill tabulate in Table (4.4), indicate that the maximum hydraulic jump efficiency was 44.503 occurred for a discharge of 5.5 lit/sec with end sill height of 5 cm and the minimum hydraulic jump efficiency of 37.014% occurred at a discharge of 1.65

lit/sec with end sill height of 3 cm. The graphical representation shown in the Fig. 4.5 (a) clearly reveal that the hydraulic jump efficiency increased with increase in the discharge with the corresponding decrease in relative loss of energy as shown in Fig 4.8 (a)

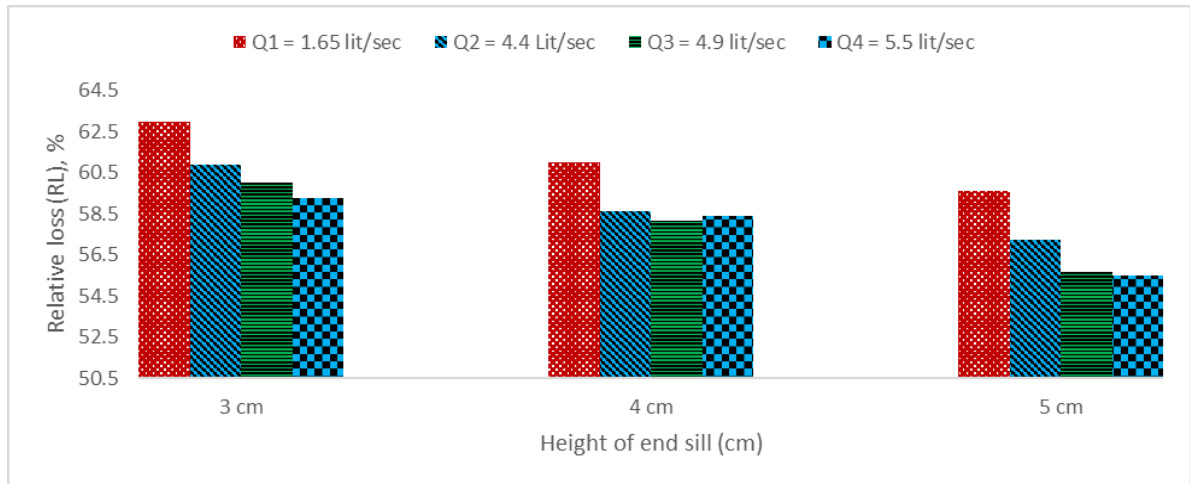
4.4.2 Relative loss of energy and hydraulic jump efficiency using different heights for triangular shape of end sill at selected discharges

The observed values of hydraulic jump efficiency and relative loss of energy were analysed and recorded in Table (4.5) for the triangular end sill (TES) of different selected height of end sill (3cm, 4 cm, and 5 cm) and selected discharge of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec. The relative loss of energy was found to be 62.966%, 61.792%, 60.380%, 59.444% and hydraulic jump efficiency was found to be 37.033%, 38.207%, 39.619%, 40.555% at corresponding discharges of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively for end sill height of 3 cm. In case of 4 cm height of end sill, the relative loss of energy and hydraulic jump efficiency were found to be 59.589%, 58.542%, 58.147%, and 38.381%, 40.410%, 41.457%, 41.852% at corresponding discharges of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively. In case of height of end sill 5 cm the hydraulic jump efficiency and relative loss of energy was found to be 38.899%, 41.083%, 42.080, 41.500% and 61.100%, 58.916, 57.919, 56.190% at selected discharges of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively.

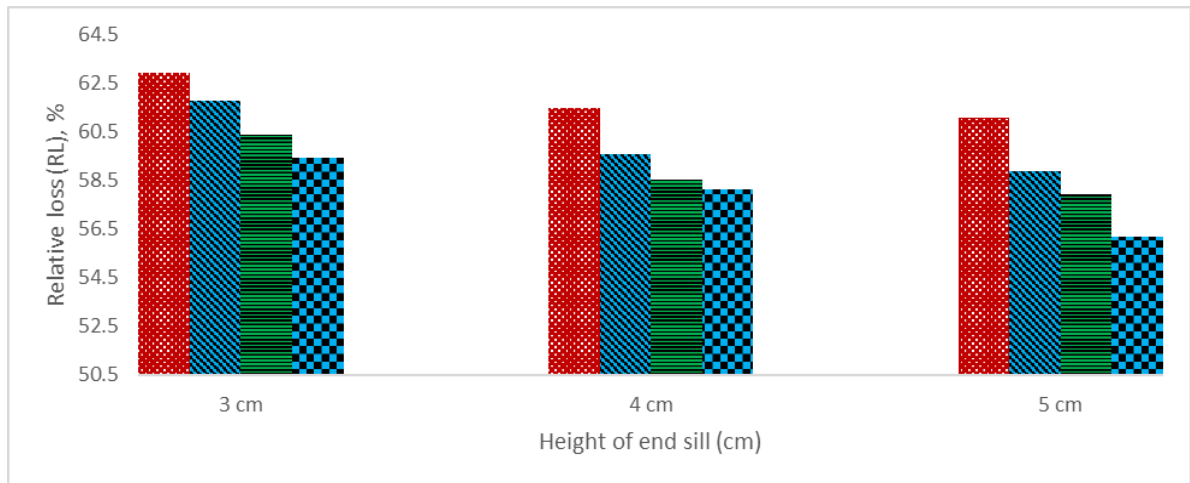
The observations recorded in Table (4.5) clearly indicate that for triangular end sill with 3cm height provided the maximum relative loss of energy of 62.966% at a discharge of 1.65 lit/sec and the minimum relative loss of 56.190% at discharge of 5.5 lit/sec with end sill height of 5 cm. The graphical representation of revealed that with the increase in discharge as well as with increasing height of end sill the relative loss of energy decreased with corresponding increase in hydraulic jump efficiency as shown in Fig 4.5 (b) and Fig. 4.8 (b).

4.4.3 Relative loss of energy and hydraulic jump efficiency using different heights for semi-circular shape of end sill at selected discharges

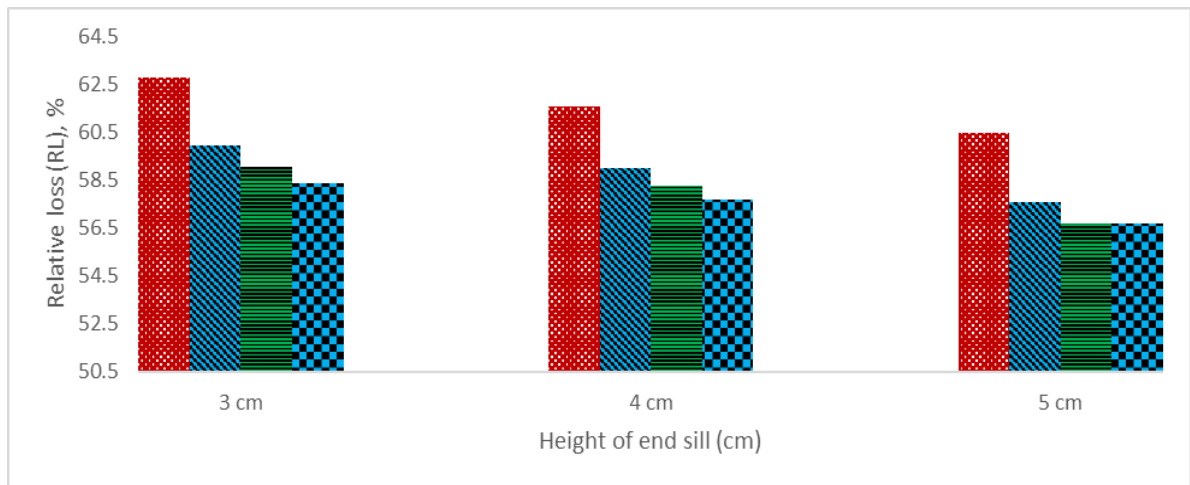
The relative loss of energy and hydraulic jump efficiency using different heights for semi-circular shape of end sill at selected discharges was observed and recorded in Table (4.6). The relative loss of energy and hydraulic jump efficiency were found to be 62.829% and 37.170% at a discharge of 1.65 lit/sec for height of end sill 3 cm. While for the discharges of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec with the height of end sill as 3 cm, the



(a) Rectangular end sill

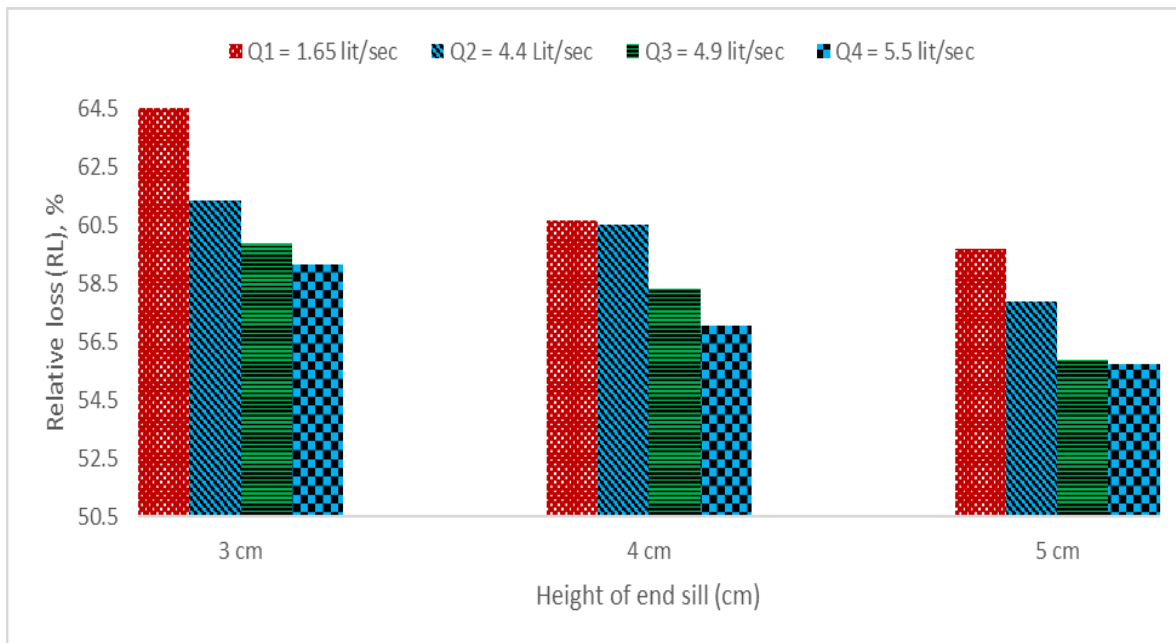


(b) Triangular end sill

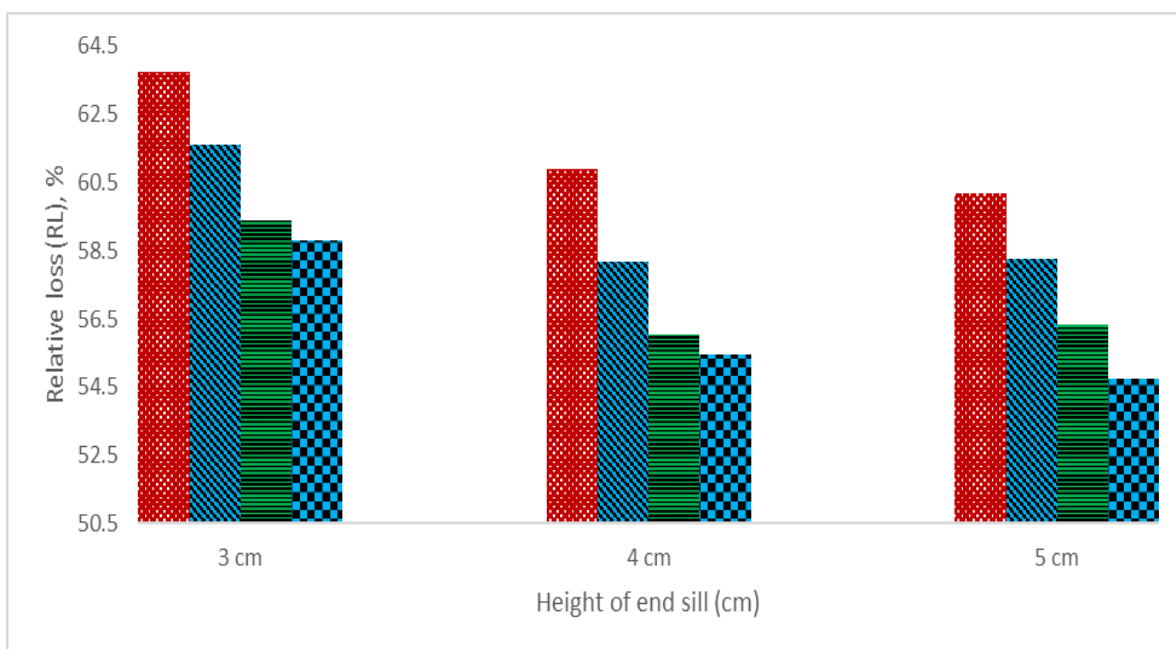


(c) Semicircular end sill

Fig. 4.8 Relative loss for rectangular, triangular and semicircular end sills at selected discharges and heights of end sill



(d) Diagonal vertical upstream end sill



(e) Diagonal vertical downstream end sill

Fig. 4.9 Relative loss for diagonal vertical upstream and diagonal vertical downstream end sills at selected discharges and heights of end sill

hydraulic jump efficiency and relative loss of energy were found to be 40.107%, 40.929%, 41.609% and 59.974%, 59.070%, 58.390% respectively. Similarly, the end sill of height 4 cm resulted in the relative loss of energy as 61.591% at a discharge of 1.65 lit/sec. The relative loss of energy and hydraulic jump efficiency were found to be 59.018%, 58.266%, 57.704% and 40.981%, 41.773%, 42.295% at discharges of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec for the same height of end sill 4 cm respectively. Similarly, In case of height of end sill as 5 cm, the hydraulic jump efficiency was found to be 39.495%, 42.381%, 43.280%, 43.293% with corresponding values of relative loss of energy as 60.504%, 57.618%, 56.719%, 56.706% at the discharges of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively for the 5 cm height of end sill.

The recorded observation presented graphically for visual comparison are shown in Fig. 4.5 (c) and 4.8 (c) for the selected discharges. From these observations it was revealed that for semi-circular end sill (SCES) the maximum hydraulic jump efficiency was found to be 43.293% and minimum at a discharge of 5.5 lit/sec and height of end sill 5 cm while the minimum hydraulic jump efficiency was found to be 37.170% at the discharge of 1.65 lit/sec with 3cm height of end sill. .

4.4.4 Relative loss of energy and hydraulic jump efficiency using different heights for diagonal vertical upstream shape of end sill at selected discharges

The hydraulic jump efficiency and relative loss of energy values were observed for diagonal vertical upstream end sill (DVUES) using different heights and discharges and recorded values are presented in Table (4.7). The recorded values clearly indicate that for diagonal vertical upstream end sill maximum hydraulic jump efficiency was found to be 44.250% for the end sill height of 5 cm for a discharge of 5.5 lit/sec and the minimum hydraulic jump efficiency of 37.117% was observed for the discharge of 1.65 lit/sec with the end sill height of 3 cm.

The hydraulic jump efficiency and relative loss of energy values are recorded in Table (4.7) for diagonal vertical upstream end sill (DVUES) of different heights (3 cm, 4 cm, and 5 cm) and selected discharge range of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec. These values indicate that in case of 3 cm height of end sill, the relative loss of energy and hydraulic jump efficiency values were found to be 68.882%, and 37.117, at a discharge of 1.65 lit/sec, while the relative loss of energy and hydraulic jump efficiency were recorded as 61.344%, 59.910%, 59.150% and 38.655%, 40.089%, 40.850% at

corresponding discharges of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively. Similarly, in case of 4 cm height of end sill the relative loss of energy was found to be 60.696%, 60.504%, 58.335% 57.051% and the hydraulic jump efficiency was found to be 39.323%, 39.490%, 41.664%, 42.943% at the discharges of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively. It was further observed that the hydraulic jump efficiency and relative loss of energy were 40.313% and 59.686% at a discharge of 1.65 lit/sec in case of 5 cm height of end sill while the hydraulic jump efficiency and relative loss of energy were observed as 42.093%, 44.083%, 44.250% and 57.906%, 55.912%, 55.749% at corresponding discharges of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively. The graphical representation of hydraulic jump makes it amply clear that the jump efficiency increased with increase in the discharge as well as the height of end sill as shown in Fig 4.6 (d).

4.4.5 Relative loss of energy and hydraulic jump efficiency using different heights for diagonal vertical downstream shape of end sill at selected discharges

Table (4.8) presents the observations of relative loss of energy and hydraulic jump efficiency for diagonal vertical downstream end sill (DVDES) of different selected heights and discharge of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec, and 5.5 lit/sec. The relative loss of energy and hydraulic jump efficiency were found to be 63.737% and 36.262% at a discharge of 1.65 lit/sec for height of end sill 3 cm. For the remaining discharges of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec the hydraulic jump efficiency and relative loss energy was found to be 38.389%, 40.588%, 41.184% and 61.160%, 59.411%, 58.815% respectively. In case of height of end sill as 4 cm, the relative loss of energy and hydraulic jump efficiency values were found to be 60.880% and 39.119% at a discharge of 1.65 lit/sec while the relative loss of energy and hydraulic jump efficiency were found to be 58.176%, 56.060%, 55.473% and 41.920%, 43.939%, 44.562% at discharges of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively. With the increase in height of end sill to 5 cm the hydraulic jump efficiency and relative loss of energy were recorded as 39.796%, 41.721%, 43.643%, 45.254% and 60.203%, 58.278%, 56.356%, 54.748% at the discharges of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively

The observation recorded in Table (4.8), clearly indicate that for all selected heights of end sill for diagonal vertical downstream end sill (DVDES) the maximum hydraulic jump efficiency was found to be 45.254% at a discharge of 5.5 lit/sec and height of end sill

5 cm and minimum hydraulic jump efficiency was found to be 36.262% at a discharge of 1.65 lit/sec and height of end sill 3 cm as shown in Fig 4.6 (e) and in Fig. 4.9 (e) for the relative loss of energy.

4.5 Height of Hydraulic Jump Using Different Shapes of End Sill with Particular Height for Selected Discharges

In the hydraulic jump analysis apart from energy dissipation, height of jump is an important parameter which decides the height of side walls to be provided in a stilling basin. Accordingly, in this study the height of jump was recorded for various combinations of end sill shape, discharge and the height of end sill. Table (4.1 to 4.3), presents the recorded values of heights of jump using different shapes of end sill for a particular height at selected discharges of 1.65 lit/sec, 4.4 lit /sec, 4.9 lit/sec and 5.5 lit/sec. The recorded data were analysed to see the effect of different shapes of end sill on height of jump as described in subsequent sections.

4.5.1 Height of hydraulic jump using different shapes for 3 cm height of end sill at selected discharges

The observed values of height of jump for this case are presented in Table (4.1). It was observed that for all selected shapes of end sill different shapes such as rectangular end sill (RES), triangular end sill (TES), semi-circular end sill (SCES), diagonal vertical upstream end sill (DVUES) and diagonal vertical downstream end sill (DVDES) of height 3 cm at selected discharges of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec the height of jump was found to be 4.336 cm at a discharge of 1.65 lit/sec for rectangular end sill, while the height of jump was found to be 4.464 cm, 4.934 cm and 4.973 cm at a discharge of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec of the same height for rectangular end sill. In case of triangular end sill the height of jump was found to be 3.900 cm at a discharge of 1.65 lit/sec, while the height of jump was recorded as 4.194 cm, 3.636 cm and 4.167 cm at a discharge of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively. For semi-circular end sill the height of jump was found to be 4.533 cm at a discharge of 1.65 lit/sec, while the height of jump was found to be 4.900 cm, 5.533 cm and 5.900 cm for the same height of end sill. The height of jump was found to be 3.933 cm, 4.300 cm, 4.666 cm and 4.450 cm at discharge of 1.65, 4.4 cm, 4.9 cm and 5.5 lit/sec respectively in case of diagonal vertical upstream end sill. The recorded values of the height of jump in case of diagonal vertical downstream end sill were found to be 3.683 cm at a discharge of 1.65 lit/sec, 3.840 cm,

4.690 cm and 5.100 cm for the corresponding discharge of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively.

The observations recorded in Table (4.1), indicate that with end sill height 3 cm for all selected shapes the maximum height of jump was found to be 5.900 cm at a discharge of 5.5 lit/sec for semi-circular and the minimum height of jump was found to be 3.63 cm for triangular end sill at a discharge of 4.90 lit/sec. It was also observed that there was no definite trend between height of jump and the discharge for selected shapes of end sill. However, it was observed that in case of rectangular end sill, semi-circular end sill (SCES) and diagonal vertical downstream end sill (DVDES) as discharge increased, the height of end sill increased for 3 cm height of end sill. In case of diagonal vertical upstream end sill, the height of jump increased when discharge was increased up to 4.4 lit/sec and then started decreasing with discharge. For triangular shaped end sill no trend was observed between height of jump and the discharge in this case. The graphical representation of height of jump for all selected end sill shapes at 3 cm height for all selected discharge is shown in Fig. 4.10 (a).

4.5.2 Height of hydraulic jump using different shapes for 4 cm height of end sill at selected discharges

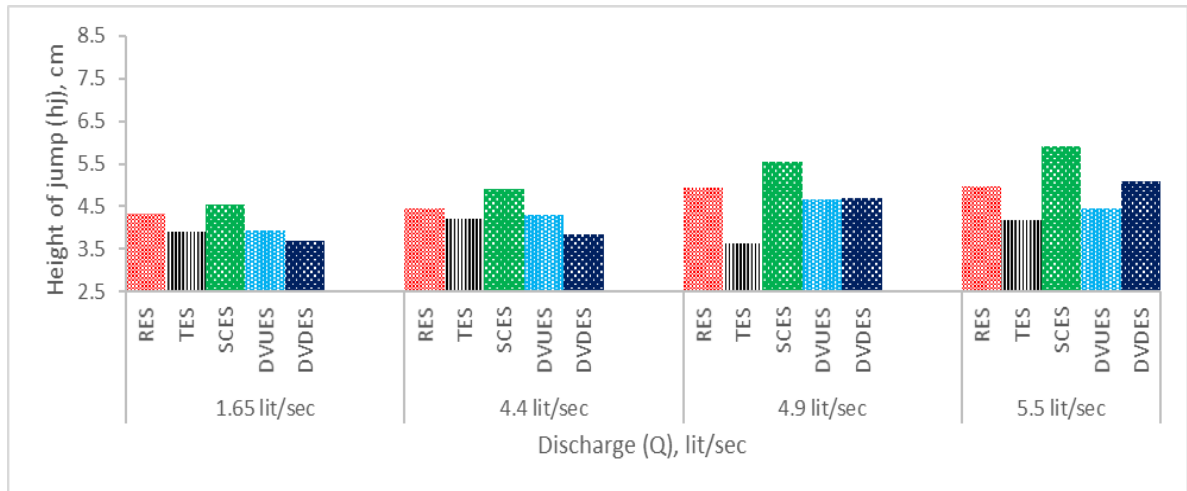
The height of jump for selected shapes of end sill of 4 cm height at discharge of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec was observed and recorded in Table (4.2). It was observed that for rectangular end sill the height of jump was found to be 5.400 cm at a discharge of 1.65 lit/sec, while for other discharges of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec, the height of jump was found to be 6.946 cm, 6.833 cm and 6.680 cm respectively. In case of triangular end sill the height of jump was recorded as 4.983 cm, 5.466 cm, 6.350 cm and 6.417 cm at discharges of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively. It was observed that that in this case height of jump was found to be increasing with increase in discharge for triangular shaped end sill of 4 cm height. Similarly for semi-circular end sill the height of jump was found to be 5.267 cm, 6.514 cm, 6.233 cm and 6.627 cm at the discharge of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively. The height of jump was recorded as 5.717 cm at a discharge of 1.65 lit/sec, while at the discharge of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec the height of jump was found to be 5.484 cm, 6.650 cm and 6.916 cm in case of diagonal vertical upstream end sill. Similarly, for the diagonal vertical downstream end sill the height of end sill was found to

Table 4.9 Observed hydraulic jump parameters and energy dissipation for different shapes and sizes of end sill at a discharge of 1.65 lit/sec

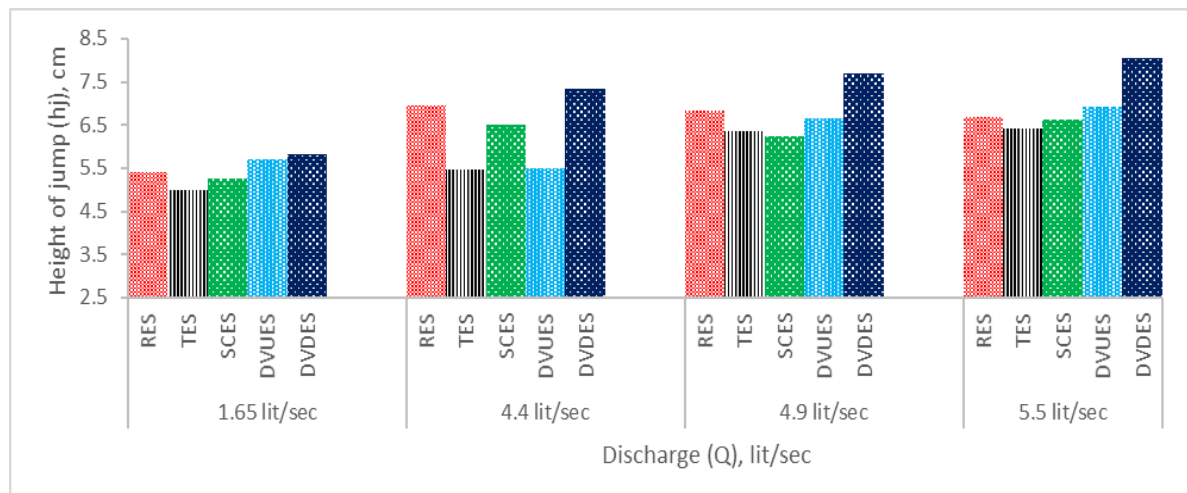
Shape of end sill	Height of end sill, cm	Depth of flow at inlet (d_i), cm	Depth of flow at outlet (d_o), cm	Flow velocity at inlet (V_i), cm/sec	Flow velocity at outlet (V_o), cm/sec	Froude number before jump (Fr_1)	Froude number after jump (Fr_2)	Flow energy at inlet (E_i), cm	Flow energy at outlet (E_o), cm	Total energy dissipation (ΔE), cm	Hydraulic jump efficiency (JE), %	Relative loss of energy (R_L), %	Height of jump (hj), cm
RES	3.00	1.833	6.166	90.160	26.759	2.127	0.344	68.973	25.530	43.432	37.014	62.965	4.333
	4.00	2.033	7.430	81.280	22.207	1.821	0.258	68.397	26.681	41.716	39.009	60.990	5.400
	5.00	1.966	8.516	83.926	19.375	1.911	0.211	68.555	27.707	40.848	40.415	59.584	6.550
TES	3.00	2.033	5.933	81.160	27.810	1.817	0.364	68.390	25.327	43.063	37.033	62.966	3.900
	4.00	2.016	7.000	81.820	23.571	1.827	0.284	68.478	26.283	42.195	38.381	61.618	4.983
	5.00	2.050	7.330	80.487	22.510	1.794	0.265	68.351	26.588	41.763	38.899	61.100	5.280
SCES	3.00	1.800	6.333	91.666	26.054	2.181	0.330	69.082	25.678	43.404	37.170	62.829	4.533
	4.00	1.733	7.000	95.210	23.571	2.309	0.284	68.430	26.283	42.147	38.408	61.591	5.267
	5.00	2.000	7.816	82.500	21.110	1.862	0.240	68.469	27.042	41.427	39.495	60.504	5.816
DVUES	3.00	2.050	5.983	80.487	27.578	1.794	0.359	68.351	25.370	42.981	37.117	68.882	3.933
	4.00	1.983	7.700	83.207	21.428	1.886	0.246	68.511	26.934	41.577	39.323	60.686	5.717
	5.00	2.080	8.330	79.326	19.807	1.758	0.219	68.287	27.529	40.758	40.313	59.686	6.250
DVDES	3.00	1.850	5.533	89.189	29.821	2.093	0.412	68.904	24.986	43.918	36.262	63.737	3.683
	4.00	1.866	7.700	88.424	21.428	2.076	0.246	68.851	26.934	41.917	39.119	60.880	5.834
	5.00	1.850	8.216	89.189	20.082	2.093	0.223	68.903	27.421	41.482	39.796	60.203	6.366

Table 4.10 Observed hydraulic jump parameters and energy dissipation for different shapes and sizes of end sill at a discharge of 4.40 lit/sec

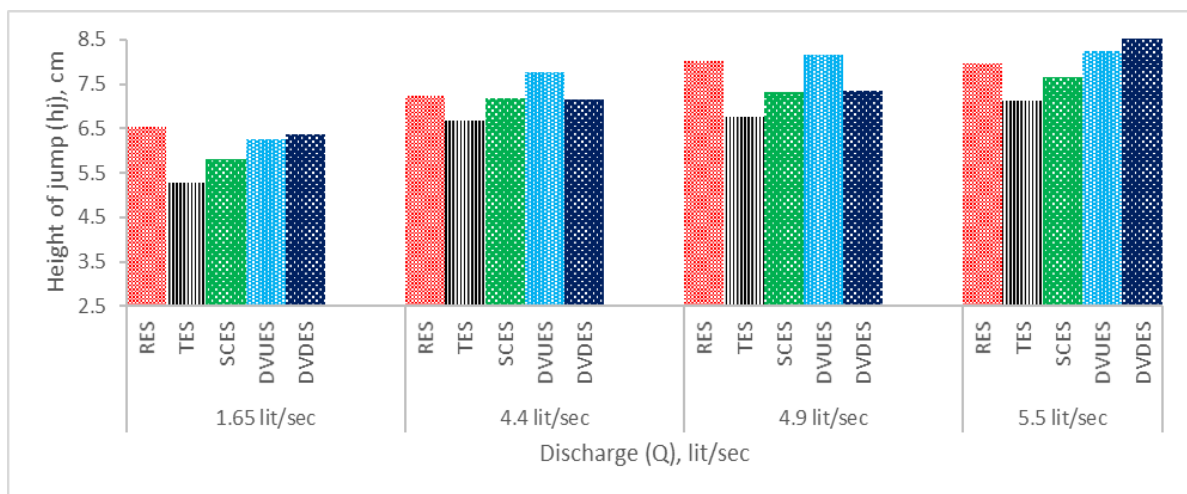
Shape of end sill	Height of end sill, cm	Depth of flow at inlet (d_i), cm	Depth of flow at outlet (d_o), cm	Flow velocity at inlet (V_i), cm/sec	Flow velocity at outlet (V_o), cm/sec	Froude number before jump (Fr_1)	Froude number after jump (Fr_2)	Flow energy at inlet (E_i), cm	Flow energy at outlet (E_o), cm	Total energy dissipation (ΔE), cm	Hydraulic jump efficiency (JE), %	Relative loss of energy (R_L), %	Height of jump (hj), cm
RES	3.00	3.866	8.330	113.812	52.821	1.848	0.584	73.468	28.752	44.716	39.135	60.864	4.464
	4.00	3.716	10.680	118.406	41.198	1.961	0.402	73.861	30.545	43.316	41.354	58.645	6.964
	5.00	4.166	11.411	105.616	38.562	1.652	0.364	72.851	31.167	41.684	42.781	57.218	7.244
TES	3.00	3.566	7.760	123.387	56.701	2.0863	0.649	74.325	28.398	45.927	38.207	61.792	4.194
	4.00	4.000	9.466	110.000	46.482	1.756	0.482	73.167	29.567	43.600	40.410	59.589	5.466
	5.00	3.733	10.416	117.867	42.242	1.947	0.417	73.813	30.325	43.488	41.083	58.916	6.683
SCES	3.00	4.133	9.033	106.460	48.710	1.672	0.517	72.909	29.242	43.667	40.107	59.974	4.900
	4.00	3.766	10.280	116.834	42.801	1.922	0.426	73.723	30.213	43.510	40.981	59.018	6.514
	5.00	4.016	11.210	109.561	39.250	1.745	0.374	73.934	30.995	42.139	42.381	57.618	7.194
DVUES	3.00	3.716	8.016	118.406	54.890	1.961	0.619	73.861	28.551	45.310	38.655	61.344	4.300
	4.00	3.616	9.100	121.681	48.351	2.045	0.511	74.162	29.291	44.871	39.490	60.504	5.484
	5.00	3.650	11.416	120.547	38.542	2.015	0.364	74.056	31.173	42.883	42.093	57.906	7.766
DVDES	3.00	3.760	7.600	117.021	57.894	1.926	0.670	73.739	28.308	45.431	38.389	61.610	3.840
	4.00	3.733	11.066	117.867	39.761	1.947	0.382	73.813	30.871	42.942	41.920	58.176	7.330
	5.00	3.766	10.933	116.834	40.245	1.924	0.388	73.723	30.758	42.965	41.721	58.278	7.167



(a) End sill height of 3 cm



(b) End sill height of 4 cm



(c) End sill height of 5 cm

Fig. 4.10 Height of jump for different shapes of end sill at selected discharges and heights of end sill

Table 4.11 Observed hydraulic jump parameters and energy dissipation for different shapes and sizes of end sill at a discharge 4.90 lit/sec

Shape of end sill	Height of end sill, cm	Depth of flow at inlet (d_i), cm	Depth of flow at outlet (d_o), cm	Flow velocity at inlet (V_i), cm/sec	Flow velocity at outlet (V_o), cm/sec	Froude number before jump (Fr_1)	Froude number after jump (Fr_2)	Flow energy at inlet (E_i), cm	Flow energy at outlet (E_o), cm	Total energy dissipation (ΔE), cm	Hydraulic jump efficiency (JE), %	Relative loss of energy (R_L), %	Height of jump (hj), cm
RES	3.00	4.266	9.200	114.861	53.260	1.775	0.560	73.990	29.645	44.345	40.066	59.933	4.934
	4.00	4.200	11.033	116.666	44.412	1.817	0.426	74.136	31.038	43.098	41.866	58.133	6.833
	5.00	4.683	12.711	104.633	38.552	1.543	0.345	73.263	32.467	40.796	44.315	55.684	8.027
TES	3.00	4.630	8.266	105.831	59.278	1.570	0.658	73.338	29.056	44.282	39.619	60.380	3.636
	4.00	4.250	10.600	115.294	46.226	1.785	0.453	74.025	30.689	43.336	41.457	58.542	6.350
	5.00	4.330	11.083	113.163	44.211	1.736	0.424	73.856	31.079	42.507	42.080	57.919	6.753
SCES	3.00	4.400	9.933	111.363	49.330	1.695	0.493	73.720	30.173	43.547	40.929	59.070	5.533
	4.00	4.433	10.666	110.534	45.940	1.676	0.449	73.660	30.741	42.919	42.773	58.266	6.233
	5.00	4.583	11.910	106.916	41.141	1.594	0.380	73.409	31.772	41.637	43.280	56.719	7.194
DVUES	3.00	4.400	9.066	111.363	54.048	1.697	0.573	73.720	29.554	44.166	40.089	59.910	4.666
	4.00	4.200	10.850	116.666	45.161	1.817	0.437	74.137	30.889	43.248	41.664	58.335	6.650
	5.00	4.500	12.660	108.888	38.704	1.639	0.347	73.543	32.423	41.120	44.083	55.912	8.160
DVDES	3.00	4.660	9.350	105.150	52.406	1.555	0.547	73.295	29.749	43.546	40.588	59.411	4.690
	4.00	4.700	12.383	104.255	39.570	1.535	0.359	73.239	32.181	41.058	43.939	56.060	7.683
	5.00	4.750	12.100	103.157	40.495	1.511	0.371	73.173	31.935	41.238	43.643	56.356	7.350

Table 4.12 Observed hydraulic jump parameters and energy dissipation for different shapes and sizes of end sill at a discharge of 5.50 lit/sec

Shape of end sill	Height of end sill, cm	Depth of flow at inlet (d_i), cm	Depth of flow at outlet (d_o), cm	Flow velocity at inlet (V_i), cm/sec	Flow velocity at outlet (V_o), cm/sec	Froude number before jump (Fr_1)	Froude number after jump (Fr_2)	Flow energy at inlet (E_i), cm	Flow energy at outlet (E_o), cm	Total energy dissipation (ΔE), cm	Hydraulic jump efficiency (JE), %	Relative loss of energy (R_L), %	Height of jump (hj), cm
RES	3.00	4.766	9.733	115.546	56.508	1.690	0.578	74.564	30.360	44.203	40.716	59.284	5.000
	4.00	4.483	11.166	122.767	49.283	1.851	0.471	75.481	31.397	44.084	41.595	58.404	6.680
	5.00	5.083	13.050	108.203	42.145	1.532	0.372	74.050	32.955	41.095	44.503	55.496	7.967
TES	3.00	5.066	9.233	108.566	59.568	1.540	0.626	74.073	30.041	44.032	40.555	59.444	4.167
	4.00	4.633	11.050	118.713	49.773	1.761	0.478	74.815	31.312	43.503	41.852	58.147	6.417
	5.00	5.230	12.350	105.162	44.534	1.468	0.404	73.866	32.360	42.320	41.500	56.190	7.120
SCES	3.00	4.766	10.666	115.400	51.565	1.687	0.504	74.553	31.021	43.532	41.609	58.390	5.900
	4.00	4.733	11.366	116.205	48.389	1.706	0.458	74.615	31.559	43.056	52.295	57.704	6.627
	5.00	4.683	12.333	117.446	44.595	1.733	0.405	74.713	32.346	42.367	43.293	56.706	7.650
DVUES	3.00	5.100	9.550	107.843	57.591	1.524	0.595	74.027	30.240	43.787	40.850	59.150	4.450
	4.00	4.900	11.816	112.244	46.547	1.618	0.432	74.321	31.920	42.401	42.949	57.051	6.916
	5.00	4.810	13.050	114.345	42.145	1.666	0.372	74.474	32.955	41.519	44.250	55.749	8.240
DVDES	3.00	4.950	10.050	111.111	54.726	1.594	0.551	74.242	30.576	43.666	41.184	58.815	5.100
	4.00	5.060	13.116	108.695	41.933	1.221	0.369	74.081	33.012	41.069	44.562	55.437	8.056
	5.00	5.116	13.666	107.505	40.245	1.517	0.347	74.006	33.491	40.515	45.254	54.748	8.550

be 5.834 cm, 7.330 cm, 7.683 cm and 8.052 cm at the selected discharge of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively.

The observation recorded in Table (4.2), indicate that for all selected shape of end sill the maximum height of jump was found to be 8.052 cm at a discharge of 5.5 lit/sec for diagonal vertical downstream end sill height 4 cm and the minimum height of jump was found to be 5.267 cm for semi-circular end sill at a discharge of 1.65 lit/sec and for all the shapes of end little variation in of height of jump was observed. From the graphical presentation shown in Fig. 4.10 (b) it was observed that the height of jump, in general, increased with discharge for all selected end sill shapes at 4 cm height.

4.5.3 Height of hydraulic jump using different shapes for 5 cm height of end sill at selected discharges

The observed values of height of jump are recorded in Table (4.3) which indicate that for all selected shapes of end sill for discharges of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec, the minimum height of jump was 5.280 cm for the discharge of 1.65lit/sec in case of triangular end sill. Similarly, the maximum height of jump was 8.550 cm for the discharge of 5.5lit/sec was observed in case of in case of diagonal vertical downstream end sill. The height of jump of rectangular shaped end sill was found to be 6.550 cm at a discharge of 1.65 lit/sec, while for the discharges of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec, the height of jump was found to be 7.244 cm, 8.027 cm and 7.967 cm respectively.

In case of triangular end sill, the height of jump was found to be 5.280 cm, 6.686 cm, 6.753 cm and 7.120 cm at the selected discharge of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec, respectively. In this case triangular and rectangular end sill the maximum height of jump was found to be 8.027 cm in case of semi-circular end sill and the height of jump of 5.816 cm was observed at a discharge of 1.65 lit/sec, while the height of jump was recorded as 7.194 cm, 7.327 cm and 7.650 cm at the discharges of 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively. For diagonal vertical upstream end sill the height of jump was recorded as 6.250 cm, 7.766 cm, 8.160 cm and 8.240 cm at discharge of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec, respectively. The height of jump was found to be 6.366 cm at a discharge of 1.65 lit/sec, which changes as 7.167 cm, 7.350 cm and 8.550 cm as discharge changed to 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively in case of diagonal vertical downstream end sill. The graphical representation as shown in Fig. 4.10 (c)



Summary & Conclusions

The use of gradient controlling structures also known as drop structures like straight drop spillways and chute spillways is very common for safe disposal of runoff water. The basic components of inclined spillway, used as permanent gully control structure are the inlet section, steep sloping channel section and the outlet section. Water enters the structure through the inlet and is conveyed through channel and leaves the structure through the outlet. When water passes through the steep sloping channel section, it acquires a very high flow velocity which results in a very high kinetic energy of flow. The flow in supercritical energy range from the channel section if allowed to pass to downstream channels without any intervention at the outlet, will cause a very serious damage (erosion) in downstream areas. As a preventive measure, this flow in its supercritical condition is passed through a stilling basin at the outlet which is designed for a dissipating the kinetic energy of flowing water to convert it to sub-critical range of energy so that the water leaving the structure does not cause much erosion in downstream areas. Stilling basins, also called as energy dissipaters, need high technical skill so as to make them more effective in terms of loss of hydraulic energy which is the difference in incoming flow energy and outgoing flow energy. These stilling basins are of various types viz. SAF stilling basin, USBR-II stilling basin, USBR-III stilling basin, baffled stilling basin, and are employed as per the existing, conditions at a place. The hydraulic energy dissipation in these stilling basins is accomplished mainly by way of turbulence through the formation of a hydraulic jump. The high velocity flow from channel section when enters a level floor of stilling basin where it meets a stream with low flow velocity a hydraulic jump is created. To create turbulence stilling basins are provided with appurtenances in the form of chute blocks, floor blocks and end sill. These appurtenances or accessories also help to stabilize hydraulic jump in a stilling basin.

End sill which is a vertical, stepped, sloped or dentate/solid wall at the downstream end of the stilling basin plays an important role in the design of stilling basin for reducing the length and it also helps to improve the flow pattern downstream of the channel. It is constructed at the downstream end of the SAF stilling basin. Its function is to reduce the length of the hydraulic jump and to control scour for large basins designed for high incoming velocities reduces. The end sill is usually dentate to perform an additional function of diffusing the residual portion of the high velocity jet that may reach the end of the SAF Stilling basin. The end sill, also helps in

deflecting the bottom currents upward and away from the stream bed. In addition, a ground roller is created under the deflected stream, which brings bed material from downstream and deposits it at the end of the stilling basin. The effect of end sill on the flow and or scour characteristics depends upon the configuration of the end sill, end sill geometry and the flow regime. The end sill height, configuration and position have great impact on the formation and control of hydraulic jump and ultimately leading to the dissipation of energy of flowing water and also to optimize the hydraulic jump length.

In this study, laboratory experiment were conducted to observe hydraulic energy dissipation behavior through the formation of hydraulic jump in an inclined spillway using SAF stilling basin. The observation were recorded using different shapes of end sill such as rectangular end sill (RES), triangular end sill (TES), semi-circular end sill (SCES), diagonal vertical upstream end sill (DVUES) and diagonal vertical downstream end sill (DVDES). These end sills were used with heights of 3 cm, 4 cm and 5 cm at selected discharge 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec. The various flow parameters were experimentally observed for 60 different combinations of end sill shape, discharge and height of end sill and compared for assessing their impact on hydraulic jump parameters.

Based on the analysis of the observed data in the present study, the following specific conclusions could be drawn.

- i. Triangular shaped end sill, it provided the maximum relative loss of energy in 07 combinations of end sill height and discharge out of total 12 combinations tried and in no case it provided the minimum energy loss.
- ii. Semi-circular, rectangular and diagonal vertical downstream shaped end sill provided minimum energy loss in 4 cases out of 12 combinations tried for each while each of them provided maximum energy loss only in one case.
- iii. The diagonal vertical upstream shaped end sill provided maximum and minimum relative energy loss in only one case each.
- iv. The triangular shaped end sill resulted in minimum height of jump, in general, for different combinations of height and discharge.

On the basis of above can therefore be concluded that the triangular shaped end sill in general, provided the maximum relative energy loss and the least height of jump for various combinations of end sill height and discharge and thus can be designated as the best performing end sill.



Literature cited

LITERATURE CITED

- Abbaspour A; Hosseinzadeh Dalir, A; Farsadizadeh, D. and Sadraddini, A.A. (2009)** Effect of sinusoidal corrugated bed on hydraulic jump characteristics Journal of Hydro-environment Research Vol. (3) 109-117
- Achour, B. and Debabeche, M. (2003)** Control of hydraulic jump by sill in triangular channel (in French) Journal of Hydraulic Research. Vol. (41) No. 3, pp. 319–325.
- Ali Abdelazim, M. and Mohamed Yasser, A. (2010)** Effect of stilling basin shape on the hydraulic characteristics of the flow downstream radial gates Hydraulic Research Institute, Journal of Alexandria Engineering, Ministry of Water Resources and Irrigation. 49(3): 393–400.
- Alikhani R; Behrozi-Rad and Fathi-Moghadam, M. (2010)** Hydraulic jump in stilling basin with vertical end sill. International Journal of Physical Sciences Vol. 5 (1), Pp. 025-029.
- Barani, G.A. (2005)** Investigation of flow energy dissipation over different stepped spillways Civil Engineering Department. Shahid Bahonar University. Kerman, Iran, pp 1101.
- Bradley, J.N. and Peterka, A.J. (1957)** Hydraulic design of stilling basins. Journal of Hydraulic Engineering. A.S.C.E, 83(5), 1401-1406.
- Bukreev, V. I. (2002)** Supercritical flow over a sill in an open channel. Journal of Applied Mechanics and Technical Physics, vol. 43, No.6, pp. 830-835.
- Chamani, M.R and Rajaratnam, N. (1999)** Characteristics of skimming flow over stepped spillway. Journal of Hydraulic Engineering. ASCE, 125(4): 361-367.
- Chanson, H; Yasuda, Y. and Ohtsu, I. (2002)** Flow resistance in skimming flow and its modelling. Journal of Civil Eng. 29(6), 809–819.
- Chinnarasri, C. and Wongwises, S. (2006)** Flow patterns and energy dissipation over various stepped chutes. Journal of Irrigation and Drainage Engg. 132(1), 70–76.

- Chow, V.T. (1959)** Open channel hydraulics. Mcgrew-Hill Book Co., New York. Engg.Vol.29 Pp. 809–819.
- Dermawan, V. and Legono, D. (2011)** Residual energy and relative energy loss on stepped spillway, Water Resource Engineering Department, Faculty of Engineering, University of Brawijaya, Malang 65145, Indonesia, 1(4) : 381-392
- Fathi Moghandam, A; Alkhani, R. and Behrozi, M. (2010)** Hydraulic jump in stilling basin with vertical end sill International Journal of Physical Sciences Vol. 5 (1), pp. 025-029.
- Flammer, G.H. and Skogerboe (2012)** Closed conduit to open channel stilling basin. Journal Irrigation and Drainage Engg. A.S.C.E: pp 96 (1), 1-11.
- Garde, R.J; Saraf, P.D. and Dahigaonkar, D.J. (1986)** Evolution of design of energy dissipators for pipe outlets, Journal of Irrigation and Power Engg. 41(3), 145-154.
- Goel, A. and Verma, D.V.S. (2000)** Stilling basins for outlets using wedge shaped splitter blocks. Journal of Irrigation and Drainage Engineering, A.S.C.E: 126 (3), 179-184.
- Hager, W.H and Bretz, N.V. (1986)** Hydraulic jump and positive and negative steps. Journal of Hydraulic Research, 24(4) : 237-248
- Hager, W.H. (1985)** Hydraulic jump in non-prismatic rectangular channels. Journal of Hydraulic Research. 23 (1): 565-585.
- Hoffman, G.J and Pilarczyk, K.W. (1995)** Local scour downstream of hydraulic structure. Journal of Hydraulic Research. 121(4) : 326-340
- Hossein, Hamidifar and Mohammad, Hossein Omid (2011)** Using a broad crested sill to control hydraulic jump in a triangular channel. Journal of Civil Engineering. 39 (2): 103-110.
- Kumar, Akhilesh; Arora, Umesh and Jain, Rajiv (2001)** Performance evaluation of hydraulic energy dissipators. Indian Journal of Soil Conservation, 29(3): 206-211.
- Kumar, Sanjeev; Gupta, R. C, Mehta, V. K. and Dwivedi (2010)** Modeling of relative length and relative energy loss of free hydraulic jump in horizontal prismatic channel. Procardia Engineering Vol. (1) pp 529 – 537.

- Lal, R. and Sohan, W. (2001)** Deforestation and land use effects on soil degradation and rehabilitation in western Nigeria. III. Run off, Soil Erosion and Nutrient Loss, Asian Association on Remote Sensing , Vol. 12, No. 6, , pp. 519-539.
- Mayas, W. and Tung, Y.K. (1982)** Optimal design of stilling basin for over flow spillways. Journal of Hydraulic Division. 108(10): 1163-1177.
- Mehdizadeh, A; Firoozabadi, B. and Sherif, S. A. (2010)** Particle trajectory study in submerged flows with baffles using turbulence models. Journal of Fluids Engineering. 132(5): 51-105.
- Meshkati, M.E; Shahmirzadi T, Sumi and Kantoush, S.A. (2014)** Energy dissipation within in ground stilling basin. International Symposium on Hydraulic Structures. 10 (4): 14-.33.
- Mohammed, T. A; Megat, M. J. and Mohd Noor, B. K. (2004)** Effect of curvature and end sill angle on local scouring at downstream of a spillway. International Journal of Engineering and Technology, Vol. 1, No. 1, pp. 96 – 101.
- Mubeen, Beg (2014)** A critical study of hydraulic jump in stilling basin with vertical end sill. Asian Journal of Science and Technology Vol. 5. pp. 369-372.
- Nanna, S. (1996)** A geo-information theoretical approach to inductive erosion modeling based on terrain mapping units. PhD thesis, Wageningen Agricultural University, Wageningen.
- Negm, A.M. (2002)** Effect of supercritical flow on scour characteristics downstream of sudden expanding stilling basins. Journal for Engineering Science and Technology Vol.6, Pp.1-13.
- Noshi, H.M. and Romish, K. (1998)** Sluiceway detail model report. Hydraulics Research Institute. Delta Barrge pp. 13621.
- Ohtsu, I. and Yasuda, Y. (2001)** Transition from supercritical to subcritical flow at an abrupt drop. Journal of Hydraulic Research, Vol. 29, No. 3, pp. 309-328.
- Othman, K. I (2008)** Scour downstream an ogee spillway. Dams & Water Resources Research Center, Mosul University 16(3).

- Patrick, F. and Laurence, Armi (2010)** Upstream internal jumps in stratified sill flow observations of formation evolution, *Journal of Physic.* 40, 1419–1426.
- Pillai, N. N. and Goel, Arun (1989)** Hydraulic jump type stilling basins for low inflow froude numbers. *Journal of Hydraulic Division, A.S.C.E:* 115, pp 989-994.
- Pirestani, M. R; Razmkhah, A. and Ghobadi, F. (2012)** Effect of convergent walls on energy dissipation in stilling basin by physical modeling. *International Journal of Thermal and Fluid Sciences.* Pp 434-564.
- Rageh, O.S. (1999)** Effect of baffle blocks on the performance of radial hydraulic jump. *Irrigation & Hydraulics Dept., Faculty of Engg. El-Mansoura University.* Vol. 62, No. 5, Pp. 32-54.
- Rajaratnam, N; Ead, and S.A. (2002)** Hydraulic jump on corrugated bed. *Journal of Hydraulic Engineering, A.S.C.E:* 128 (7), 656-663.
- Rajaratnam, N; Habibzadeh, A. and Loewen, M. R. (2012)** Performance of baffle blocks in submerged hydraulic jumps. *Journal of Hydraulic Engineering. A.S.C.E:* pp587. 902–908.
- Rand, W. (1965)** Flow over a vertical sill in an open channel. *Journal of Hydraulic Division, A.S.C.E,* Vol. 91, No. 4, Pp. 97-121.
- Riyadh, Z. and Ali, Zubaidy (2014)** Energy dissipation by using different sizes and configurations of direction diverting blocks on spillways. *Journal of Babylon University/Engineering Sciences.* No. (2) Vol.(22).
- Sameh, A. and Kantoush (2010)** Geometry effect on flow and sediment deposition patterns in shallow basins. *Journal of Hydraulic Engg. A.S.C.E:* Vol. (5).
- Sorensen, R. M. (1985)** Stepped spillway hydraulic model investigation. *Journal of Hydraulic Research Engineering. A.S.C.E:* 111(12):1461-1472.
- Tiwari, Gahlot and Verma. (2010)** Stilling basins below outlet works an overview. *International Journal of Engineering Science and Technology* Vol. 2(11), 6380-6385.

- Tiwari, H.L. (2013)** Analysis of baffle wall gap in the design of stilling basin models. International Journal of Civil Engineering and Technology. 4 (4), Pp.66-71.
- Tokyay, N.D. (2005)** Effect of channel bed corrugations on hydraulic jumps in impacts of global climate change conference. Alaska, USA, pp. 408-416.
- Toombes, L. And Chanson, H. (2000)** A comparative study of smooth and stepped chutes air–water flow and gas transfer at aeration cascades In Minor, W.H. Proceedings of the International Workshop on Hydraulics of Stepped Spillways, Pp. 77–84.
- Verma, D.V.S. And Goel, A. (2003)** Development of efficient stilling basins for pipe outlets. Journal of Irrigation and Drainage Engg. A.S.C.E: 129(3), 194-200.
- Warren Frizell, K. (2009)** Stilling basin performance for stepped spillways of mild to steep slopes Type III Basins. Hydraulic Investigations and Laboratory Services. pp 1445-2145
- Wood, I. R; Ackers, P. and Loveless, J. (1983)** General model for critical point on spillways. Journal of Hydraulic Engineering, A.S.C.E: 109(2): 308-312.



Appendices

Table 4. Comparative performance of end sill with various combinations of height and discharge

RES			TES		SCES		DVUES		DVDES	
Discharge, Height	Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest
Q ₁ ,h ₁	—	—	—	—	—	✓	—	—	✓	—
Q ₁ ,h ₂	—	—	✓	—	—	—	—	✓	—	—
Q ₁ ,h ₃	—	✓	✓	—	—	—	—	—	—	—
Q ₂ ,h ₁	—	—	—	—	—	✓	—	—	—	—
Q ₂ ,h ₂	—	✓	—	—	—	—	✓	—	—	✓
Q ₂ ,h ₃	—	✓	✓	—	—	—	—	—	—	—
Q ₃ ,h ₁	—	—	✓	—	—	✓	—	—	—	—
Q ₃ ,h ₂	—	—	✓	—	—	—	—	—	—	✓
Q ₃ ,h ₃	—	✓	✓	—	—	—	—	—	—	—
Q ₄ ,h ₁	—	—	✓	—	—	✓	—	—	—	—
Q ₄ ,h ₂	✓	—	—	—	—	—	—	—	—	✓
Q ₄ ,h ₃	—	—	—	—	✓	—	—	—	—	✓

The author of this manuscript was born on 15 June 1990 at Baidaula Garh, Domaria Ganj city of Siddharth Nagar in the state of Uttar Pradesh. He passed his High School Examination in 2004 from Kisan Inter College Bhanpur, Basti and cleared his Intermediate Examination in 2006 from Ratan Sen Inter College Bansi, Siddharth Nagar. He earned his B.Tech. (Agricultural Engineering) Degree from Shivdan Singh Institute of Technology & Management, Aligarh affiliated from Uttar Pradesh Technical University Lucknow in 2013. He joined the M.Tech. Degree programme in Agricultural Engineering with major in Soil and Water Conservation Engineering at Govind Ballabh Pant University of Agriculture and Technology, Pantnagar in August 2013.

Address:

Shatruhan Jaiswal
S/o Late Sh. Saltan Prasad Jaiswal
Home No. 77
Baidaula Garh, Domaria Ganj
District - Siddharth Nagar, Pin- 272189
Uttar Pradesh
Contact Number, 9557379162

E. Mail; sonujaiswal97@gmail.com

Name : Shatruhan Jaiswal Id. No. 45822
Semester Year of admission : 01st 2013-14 Degree: M. Tech. (Agril. Engg.)
Major : Soil and Water Conservation Engineering
Department : Soil and Water Conservation Engineering
Thesis title : **EFFECT OF SHAPE AND SIZE OF END SILL ON HYDRAULIC ENERGY DISSIPATION BEHAVIOR IN INCLINED SPILLWAY**
Advisor : Dr. Akhilesh Kumar

ABSTRACT

In this study laboratory experiments were conducted to observe hydraulic energy dissipation behaviour through the formation of hydraulic jump in an inclined spillway with SAF stilling basin using different shapes and sizes of end sill for varying discharge conditions. In all cases the total drop was kept constant. The observation were recorded using different combinations of height and shapes of end sill such as rectangular end sill (RES), triangular end sill (TES), semi-circular end sill (SCES), diagonal vertical upstream end sill (DVUES) and diagonal vertical downstream end sill (DVDES). These end sills were used for three heights of 3 cm, 4 cm and 5 cm at selected discharges of 1.65 lit/sec, 4.4 lit/sec, 4.9 lit/sec and 5.5 lit/sec respectively. Required flow parameters like pre and post jump depth of flow, height of jump were experimentally observed for 60 different combinations of end sill shape, discharge and height of end sill. Based on these observations, pre and post jump flow energy was determined and accordingly amount of relative loss of energy, hydraulic jump efficiency were calculated and compared.

It was observed that in case of triangular shaped end sill, the maximum relative loss of energy occurred in 07 combinations of end sill height and discharge out of total 12 combinations tried and in no case it provided the minimum energy loss. Similarly, semi-circular, rectangular and diagonal vertical downstream shaped end sill provided minimum energy loss in 4 cases out of 12 combinations tried for each while each of them provided maximum energy loss only in one case. The diagonal vertical upstream shaped end sill provided maximum and minimum relative energy loss in only one case each. It was also found that the triangular shaped end sill resulted in minimum height of jump, in general, for different combinations of height and discharge.



Dr. Akhilesh Kumar
(Advisor)



Shatruhan Jaiswal
(Author)

नाम : शत्रुहन जायसवाल **परिचयांक:** 45822
प्रवेश वर्ष : 2013-14 **उपाधि:** स्थानकोत्तर (कृषि अभियांत्रिकी)
मुख्य विभाग : मृदा एवं जल संरक्षण अभियांत्रिकी
शोध प्रबंध शीर्षक : झुका हुआ उत्प्लव के जलीय ऊर्जा पर अंत शिला के आकृति और आकार का प्रभाव
सलाहकार : डा. अखिलेश कुमार

सारांश

इस प्रयोगशाला में प्रयोगों के अध्ययन से बदलती निर्वहन के लिए अंत शिला के अलग-अलग आकृति और आकार का उपयोग कर के एस. ए. एफ. स्टीलिंग बेसिन के साथ जलीय ऊर्जा के लंपटता व्यवहार के एक उत्प्लव मार्ग में जलीय कूद के गठन के माध्यम से पालन करने के लिए आयोजित किए गए। इन सभी मामलों में कुल गिरावट स्थिर रखा गया था। अवलोकन दर्ज की ऊँचाई के विभिन्न संयोजनों और आकार में जैसे, आयताकार अंत शिला (आर0 ई0 एस0), त्रिकोणीय अंत शिला (टी 0 ई0 एस0), अर्द्ध वृत्तीय अंत शिला (एस 0 सी0 ई0 एस0), विकर्ण ऊर्ध्वाधर प्रतिकूल अंत शिला (डी0 वी0 यू0 ई0 एस0) और विकर्ण ऊर्ध्वाधर विपरीत अंत शिला (डी 0 वी0 डी0 ई0 एस0) जैसे अंत शिला का उपयोग कर रहे थे। ये अंत शिला क्रमशः तीन ऊंचाइयों जैसे 3 से0मी0, 4 से0मी0 और 5 से0मी0, प्रवाह जैसे, 1.65 लीटर/से0, 4.4 लीटर/सेकंड, 4.9 मी0³/सेकंड और 5.5 लीटर/सेकंड के चयनित प्रवाह के लिए इस्तेमाल किया गया। प्रवाह के पहले और बाद जैसे आवश्यक कूद की गहराई, प्रवाह पैरामीटर, कूदने की ऊंचाई, अंत शिला आकार, और अंत शिला की ऊंचाई की जैसे 60 विभिन्न संयोजनों के लिए बनाया गया। इन टिप्पणियों के आधार पर पहले और बाद जलीय ऊर्जा और जलीय कूद दक्षता को निर्धारित किया गया था ऊर्जा हानि की तदनुसार राशि की गणना और तुलना की गई।

यह त्रिकोणीय आकार का अंत शिला अधिकतम ऊर्जा हानि मामले में, अंत शिला की ऊंचाई और प्रवाह के कुल 12 संयोजनों में से 07 संयोजनों में पाया गया। इसी प्रकार, अर्द्ध वृत्तीय, आयताकार और विकर्ण ऊर्ध्वाधर विपरीत में कुल 12 संयोजनों में से 04 संयोजनों में न्यूनतम ऊर्जा हानि पाया गया। और सभी संयोजनों में से प्रत्येक के एक मामले में अधिकतम ऊर्जा नुकसान केवल एक में प्रदान की। यह भी पाया गया कि त्रिकोणीय आकार का अंत शिला के परिणामस्वरूप में कूद की ऊंचाई न्यूनतम था।

संस्करण के आधार पर त्रिकोणीय आकार का अंत शिला सामान्य, में अधिकतम सापेक्ष ऊर्जा की हानि और अंत शिला ऊंचाई के विभिन्न संयोजनों के लिए कम से कम कूदने की ऊंचाई प्रदान की और इसलिए निष्कर्ष निकाला गया कि त्रिकोणीय अंत शिला प्रदर्शन के रूप में नामित किया जा सकता है।



डा. अखिलेश कुमार
 (सलाहकार)



शत्रुहन जायसवाल
 (लेखक)